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Development of Performance Data for Common Building Air Cleaning Devices

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FINAL REPORT ON

Development of Performance Data for Common Building Air Cleaning Devices

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Prepared for

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U.S. ENVIRONMENTAL PROTECTION AGENCY

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BATTELLE COLUMBUS OPERATIONS

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List of Acronyms

ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BG	*Bacillus globigii*
CB	chemical or biological
CDC	Centers for Disease Control and Prevention
CFM	cubic feet per minute
CFU	colony forming unit
COTR	contracting officer's technical representative
CT	time-integrated concentration (concentration*time)
CV	coefficient of variation
E1	average efficiency for particles with physical diameters between 0.3 μm and 1 μm
E2	average efficiency for particles with physical diameters between 1 μm and 3 μm
E3	average efficiency for particles with physical diameters between 3 μm and 10 μm
EAC	electronic air cleaner
EPA	Environmental Protection Agency
ETV	Environmental Technology Verification
fpm	feet per minute
g	grams
HEPA	high efficiency particulate air
HVAC	heating, ventilation, and air conditioning
in	inches
in. w. g.	inches of water gauge
inHg	inches of mercury
KCl	potassium chloride
MERV	minimum efficiency reporting value
NA	not available
OPC	optical particle counter
ORD	Office of Research and Development
PBS	phosphate-buffered saline
PSI	pounds per square inch
QA	quality assurance
QAPP	Test/Quality Assurance Project Plan
SMPS	Scanning Mobility Particle Sizer
SOP	standard operating procedure
SOW	statement of work
TSA	tryptic soy agar
μm	micrometer

Executive Summary

Recent events have shown that buildings are vulnerable to terrorist attacks involving biological agents. The most serious effects of such an attack are on the health of the occupants of the buildings. Building occupants may suffer health effects ranging from irritation to severe sickness to death. An attack may also have long-term economic and other impacts due to contamination of the building. Several organizations, including the Army Corps of Engineers, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), and the Centers for Disease Control and Prevention (CDC), recognize this terrorist threat and have issued guidance documents on how to deal with it. These documents, while useful, suffer from the fact that the scientific, engineering, and economic information needed to determine optimum courses of action is inadequate. The tools and technologies required to implement optimum courses of action are often not available, are too expensive to use, or are inadequate.

The work described in this document was performed under a broader project to investigate building air cleaning systems' effectiveness in protecting buildings from terrorist attacks with biological agents. This report in particular describes the results of an effort to collect performance data (pressure drop and collection efficiency for biological and non-biological aerosols) on 24 commonly used ventilation filters and on three commercially available electronic air cleaners (EACs). For both sets of air cleaners, tests were performed with both "off-the-shelf" units and with a selected subset of units aged in a typical or simulated use environment to allow a better understanding of how the units would likely perform over their entire service lives. In addition, testing was performed on a select subset of units against a bioaerosol to demonstrate the similarity in performance between inert and biological particles. Empirical equations were developed that relate particle collection efficiency to particle physical diameter over the range of 0.03 to 10 µm, which can be incorporated into indoor air quality models.

Results from Inert Aerosol Evaluations of "Off-the-Shelf" Filters

The measured pressure drops of the "off-the-shelf" filters generally corresponded quite well (± 30%) with the information provided by the vendors, although, in a few cases, the measured pressure drops were somewhat greater. With the exception of several Minimum Efficiency Reporting Value (MERV) 11 filters, the MERV ratings that were determined from the tests were generally equivalent or within one or two MERV ratings reported by the manufacturer. The testing during this study consisted of evaluating single filters; therefore, the results may not be representative of typical performance. (Note: The ANSI/ASHRAE 52.2-1999 standard does not provide any guidance as to the number of samples of a filter type that should be tested to ensure that the manufacturer-reported MERV rating provides a statistically reasonable representation of their performance.)

For the filters tested, which covered all of the MERV ratings, collection efficiencies determined from measurements made with the Climet model 500 Spectrometer optical particle counter (OPC) (0.3 to 10 µm) generally corresponded very well with the collection efficiencies determined using the TSI Scanning Mobility Particle Sizer (SMPS) (0.03 to 0.3 µm). The most penetrating particle size was consistently in the 0.1 to 0.3 µm range, which is consistent with typical filtration efficiency curves. Table ES-1 provides a summary of the results from the inert aerosol evaluations of unconditioned, unaged ("off-the-shelf") filters. As shown in Table ES-1, the pressure drops of the filters

Table ES-1. Summary of the Results from the Inert Aerosol Evaluations and Curve Fits of Unaged Unconditioned Air Filters

MERV Rating	Number of Filters Tested	Average Pressure Drop (in. of water) at 370 fpm	Predicted Collection Efficiencies from Curve Fits (%)					
			0.03 µm	0.1 µm	0.3 µm	1.1 µm	3.5 µm	8.4 µm
5	1	0.24	13	0	5	24	34	34
6	2	0.22 ± 0.06	12	6	5	16	35	53
7	6	0.30 ± 0.08	44	13	20	47	61	65
8	4	0.26 ± 0.03	40	20	22	52	75	86
10	1	0.29	55	37	29	53	85	97
12	5	0.46[a] ± 0.09	71	47	49	78	95	99
14	4	0.48[b] ± 0.11	82	59	68	93	99	99
16	3	0.73 ± 0.15	99	95	96	99	99	99
16+ (HEPA)	1	0.97	>99	>99	>99	>99	>99	>99

[a] – neglecting electrostatic filter 4FUA-12-3, which had a pressure drop of only 0.13 inches of water

[b] – neglecting filter C6-ADP-15-1, which was evaluated well above its nominal flow rate

between MERV 5 and 10 at 370 feet per minute (fpm) did not appear to be substantially different, with a good deal of overlap between the average pressure drops. However, there was a significant increase in pressure drops between the MERV 10 and MERV 12 filters, between the MERV 14 and MERV 16 filters, and between the MERV 16 filters and the HEPA (MERV >16) filter. As expected, the collection efficiency of the filters generally increased with MERV rating. Therefore, consumers of air filters will need to balance the higher pressure drops and cost of MERV 12 to MERV 16 filters with the expected increase in performance.

Table ES-2 lists the results from the curve fitting analysis (the development of equations to predict particle penetration as a function of particle size, based on the experimental data) for the "off-the-shelf" filters. As shown in Table ES-2, all but one of the curve fits possessed correlation coefficients (r squared) greater than 0.89, indicating an excellent representation of the data. The MERV 6 curve fit possessed a lower correlation value of 0.83. In all cases, it is not recommended that the equations be extrapolated outside of the particle size range used (0.03 to 10 µm). These curve fits provide a valuable tool that will enable consumers to accurately estimate the collection efficiency of a filter with a given MERV rating to determine whether its likely performance will justify its increased cost and pressure drop.

Table ES-2. Summary of the Results from the Curve Fits to the Inert Aerosol Evaluations of Unaged Unconditioned Air Filters

MERV Rating	Equation	Parameters	Correlation Coefficient (r^2)
5	$Y = a + bx + cx^2 + dx^3$ where Y = log of percent penetration x = log of particle diameter	a = 1.8906 b = –0.1722 c = 0.0307 d = 0.0793	0.8935
6	$Y = a + bx + cx^2 + dx^3$ where Y = log of percent penetration x = log of particle diameter	a = 1.9311 b = –0.1441 c = –0.1243 d = –0.0234	0.8332
7	$Y = a + bx + cx^2 + dx^3$ where Y = log of percent penetration x = log of particle diameter	a = 1.7467 b = –0.3314 c = –0.0036 d = 0.1381	0.9064
8	$Y = a + bx + cx^2 + dx^3$ where Y = log of percent penetration x = log of particle diameter	a = 0.5839 b = 0.1675 c = 0.1289 d = 0.0188	0.9658
10	$Y = a + bx + cx^2 + dx^3$ where Y = log of percent penetration x = log of particle diameter	a = 1.7083 b = –0.5759 c = –0.6721 d = –0.1775	0.9852
12	$Y = a + bx + cx^2 + dx^3$ where Y = log of percent penetration x = log of particle diameter	a = 1.3943 b = –0.9080 c = –0.6240 d = –0.0404	0.9902
14	$Y = a + bx + cx^2 + dx^3$ where Y = log of percent penetration x = log of particle diameter	a = 0.9531 b = –1.4941 c = –0.8443 d = –0.0013	0.9668
16	$\ln Y = a + bx + cx^2 + dx^3$ where Y = percent penetration x = log of particle diameter	a = 0.3855 b = –2.0698 c = 0.5326 d = 1.3895	0.9728
16+ (HEPA)	$Y = a + bx + cx^2 + dx^3 + ex^4$ where Y = percent penetration x = log of particle diameter	a = 0.0361 b = –0.3506 c = 0.5119 d = 0.0481 e = –0.1816	0.8917

Table ES-3. Summary of the Results from the Curve Fits to the Inert Aerosol Evaluations of Unaged Unconditioned Electronic Air Cleaners

MERV Rating	Equation	Parameters	Correlation Coefficient (r^2)
14 and 15 (all unaged unconditioned EACs)	$Y = a + bx + cx^2 + dx^3$ where Y = log of percent penetration x = log of particle diameter	a = 0.8422 b = – 0.6469 c = – 0.2157 d = 0.1645	0.9600

Results from Inert Aerosol Evaluations of "Off-the-Shelf" Electronic Air Cleaners

The measured pressure drops of two of the three tested units (A and P) corresponded well with the information provided by the manufacturers, while the pressure drop for Unit H was nearly double the expected value. The measured pressure drops for the EACs averaged 0.14 $\pm$ 0.03 inches of water at 370 feet per minute, which is approximately one-half that of the average pressure drop for MERV 5 to 10 filters. Given that the EACs possessed MERV ratings of 14 and 15, at least initially, they appeared to offer considerably higher collection efficiency than air filters for a given pressure drop. In terms of collection efficiency, the MERV ratings that were determined from the tests ranged from one MERV rating below to three MERV ratings above the manufacturer-reported value. Note that the testing during this study consisted of evaluating pairs of units; therefore, the results may not be representative of typical performance. As with the filters, collection efficiencies determined with the OPC (0.3 to 10 µm) generally corresponded very well with the collection efficiencies determined using the SMPS (0.03 to 0.3 µm). A single curve was fit with an excellent correlation (r squared value of 0.96) to all of the "off-the-shelf" EAC results; the results are listed in Table ES-3. This empirical model may be used for predicting the likely collection efficiency of an electronic air cleaner with a MERV rating of 14 or 15.

Results from Bioaerosol Evaluations of "Off-the-Shelf" Filters and Electronic Air Cleaners

A select group of filters (seven) and EACs (three) were evaluated against a bioaerosol challenge. The purpose of the bioaerosol tests was to compare the penetration of a bioaerosol to the penetration of a similarly-sized inert aerosol to determine whether there were any significant differences between the penetration of bioaerosol and inert particles.

Similar to previously reported results (RTI, 2004), in nine of the ten tests, the measured bioaerosol collection efficiencies generally exceeded the average collection efficiency for inert particles with physical particle diameters between 0.3 and 1 µm but were generally less than or equivalent to the inert aerosol collection efficiency results for 1- to 3-µm particles. For the remaining filter (6DDUE-8), only a 6% collection efficiency was measured but with a large standard deviation. When the standard deviation is taken into consideration, the test results are likely in reasonable agreement. Overall, the results indicate that the collection efficiency for bioaerosol particles is similar to comparably sized inert particles.

Results from Aging Evaluations of "Off-the-Shelf" Filters

For a select group of filters (seven), simulated aging tests were performed with inert aerosols to examine the effect of dust loading in actual use environments on the collection efficiencies and pressure drops of the units.

For the two electrostatic residential filters (6DDUE-8 and 8NM-10), the collection efficiency for larger particles (3.0 to 10.0 µm) either increased significantly (6DDUE-8) or remained the same (8NM-10) after the filters started to be loaded with particles. However, for both filters, a substantial decrease in collection efficiency was noted for smaller particles (0.3 to 3 µm) after the filters were loaded. The collection efficiency of the filters for smaller particles did not exceed the initial efficiency until between 8 and 12 weeks of loading had occurred. The pressure drops of both residential filters remained fairly consistent through the first 8 weeks of use; the pressure drop then increased greatly between weeks 8 and 12. It should be noted that 12 weeks of use constitutes 100% of the manufacturer-recommended service time for these two filters.

Similarly, the two electrostatic commercial prefilters (C17FPP-8 and C15AAA-11) demonstrated consistent average collection efficiencies for larger particles (4.0 to 10.0 µm) over the entire 16-week test. However, there was a very substantial drop in collection efficiency for particles smaller than approximately 4 µm once the loading began, and the collection efficiency for the smaller particles never returned to the measured initial values. The pressure drops of the two prefilters did not demonstrate any noticeable increase over the aging period. The typical service life for prefilters in the HVAC system of interest ranges from 3 to 6 months, so the 4 months of aging that was performed represented between 67% and 133% of a typical service period. It should be noted that the performance of Filter C15AAA-11 was considerably poorer than was expected from the manufacturers literature.

In contrast, the 12-inch deep electrostatic commercial box filter (C8GZ-13) substantially degraded in collection efficiency for all particle sizes over the entire aging period, dropping steadily from MERV 12 to MERV 10. No change in pressure drop occurred over this period, implying that a suitable dust cake did not form during loading, which would likely have caused the degradation of collection efficiency to slow. The range of service life for filter C8GZ-13 in the application of interest is 6 to 12 months, with typical usage closer to 12 months, so the aging period represented only 33% to 67% of the typical service life.

As expected, the two commercial, 12-inch deep, non-electrostatic, traditional fiberglass media deep-pleated filters (C14PCS and C11GM-16) did not demonstrate any degradation in collection efficiency during the aging period. In fact, the collection efficiency of Filter C14PCS clearly increased as dust was collected on the filter during aging. No change in pressure drop was noted over the aging period for these two filters. The typical service life for these two filters in the application of interest is 6 to 12 months (typically closer to 12 months), so the aging period represented only 33% to 67% of the typical service life.

Results from Aging Evaluations of "Off-the-Shelf" Electronic Air Cleaners

For the EACs (three), aging was performed using an inert aerosol to examine the effect of dust loading in actual use environments on the collection efficiency and pressure drop of the units. Cleaning was not performed over the entire aging duration. This was consistent with the manufacturers' recommendations of cleaning intervals between 1 and 6 months in duration. The manufacturers' literature recommended cleaning only when a visual inspection indicated that one was required.

As expected, the pressure drops of all three units remained consistent over the entire aging period. Unit A demonstrated nearly no degradation in performance over the entire 2,016 hour aging period, having just a minor decrease in the average efficiency for 0.3- to 1-μm particles (from 87.6% to 80.7%).

Unit H performed reasonably well but showed more degradation than Unit A, dropping from a MERV 15 to a MERV 12 over the aging period. While the MERV rating remained consistent for the first 1,008 hours of aging, after 2,016 hours of operation, its MERV rating dropped to 12, indicating that cleaning after 84 days of continuous operation was warranted.

In contrast, Unit P dropped precipitously from a MERV 14 to a MERV 6 between 336 hours and 1,008 hours of use. Despite the significant drop in collection efficiency, the visible buildup on the unit was not substantial enough to clearly warrant cleaning. Unit P was not visibly dirtier than the other two units, so the user would have no reason to suspect that performance had substantially degraded. However, based on its collection efficiency, cleaning of Unit P would be recommended after 14 days of continuous use.

Results from Conditioning Evaluations of "Off-the-Shelf" Filters

Eight filters (all electrostatic) were evaluated using an inert aerosol test method that involved conditioning the filter with submicron potassium chloride particles to identify the loading or conditioning level that resulted in the minimum collection efficiency. The test method used was from the draft Addendum C to ANSI/ASHRAE Standard 52.2-1999. The purpose of the conditioning tests was to compare results with the aging tests to determine whether the draft Addendum C test method provided a suitable means for accurately simulating the performance over time of an electrostatic filter in a typical use environment.

Four of the residential electrostatic filters performed similarly during the conditioning evaluations. Upon conditioning, the collection efficiency increased significantly for particles larger than approximately 1 to 2 μm but appeared to decrease slightly or remain constant for particles smaller than 1 to 2 μm. This was consistent with the observed trend during the aging tests of one of the residential filters, during which the collection efficiency increased upon aging for particles larger than 4 μm but decreased significantly for particles smaller than 2 μm.

For a fifth residential filter, the collection efficiency decreased slightly for all particles upon initial conditioning but increased for all particles once the equivalent of 1 month of conditioning had been performed. This trend was similar to the results observed during the aging tests for the same filter, although the decrease in collection efficiency was more substantial and required approximately 12 weeks of aging for the collection efficiency to increase past the initial values.

The aging and conditioning tests of one commercial prefilter also appeared to be consistent. Conditioning of the commercial prefilter resulted in a noticeable decrease in collection efficiency for all particles less than approximately 1 μm, with no recovery during the approximately 1 month equivalent of conditioning. Aging of the prefilter also resulted in a decrease (although more substantial) in collection efficiency for all particles smaller than approximately 4 μm, with no recovery over 16 weeks of aging.

In contrast, the aging and conditioning tests of the remaining two commercial filters did not produce consistent results. For a commercial prefilter, the collection efficiency increased slightly for all particles upon initial conditioning and remained at the same level with further conditioning. This result noticeably contrasted with the results from the aging evaluations, in which the collection efficiency decreased substantially for particles smaller than 4 μm with aging and did not increase over 16 weeks of use. For a commercial box filter, the results from the aging and conditioning evaluations contrasted even more strongly. In the conditioning evaluation, the collection efficiency remained essentially constant during the approximately 1 month equivalent of conditioning, even increasing slightly for particles smaller than 0.3 μm. However, during the entire 16 weeks of aging, the box filter consistently and continually decreased in collection efficiency for all particles.

It is not known why the trends in the results from the conditioning evaluations are consistent with the aging results for some but not all of the filters. Further investigation of these contrasting results seems warranted but was beyond the scope of this effort. It should be noted that during the conditioning evaluations, only a single filter of each type was tested. In contrast, the aging evaluations were performed with five different filters of identical make, model, and size. Therefore, some variability is present in the aging evaluations due to the different performance levels of the individual filters, whereas the analysis of variability for the conditioning tests for a particular type of filter is not feasible.

Results from Conditioning Evaluations of "Off-the-Shelf" Electronic Air Cleaners

Three EACs were evaluated both before and after conditioning with silicon vapor. The purpose of the exposure to silicon vapor was to determine whether this conditioning approach resulted in filter performance similar to the performance of the EACs after one month of actual use.

The exposure of Units A and P to silicon vapor appeared to cause a very similar level of degradation in performance compared to that likely to be observed after 1 month of ambient aging (672 hours of use). For both of these units, the collection efficiency of the EAC degraded more than that observed during 336 hours (2 weeks) of ambient use but less than that observed after 1,008 hours (6 weeks) of ambient use.

For Unit H, however, the silicon vapor exposure degraded the unit's performance well beyond that observed after even 2,016 hours of ambient aging (12 weeks of continuous operation).

It is not known why the results from the aging and conditioning evaluations are consistent for units A and P but inconsistent for Unit H. It could be a result of design and component differences between the three units. Given the approximately 50% decrease in pressure drop in Unit H after silicon vapor exposure, and the alteration in the shape of the collection efficiency curve, it is possible that the exposure allowed leakage to occur within the unit. Further investigation of the contrasting results for Unit H seems warranted but was beyond the scope of this effort.

It should be noted that in contrast to the filter evaluations, during the EAC aging evaluations, a single unit was used. Therefore, no variability data are available for the EAC aging evaluations.

Recommendations

As a result of this effort, empirical models (curve fits) are now available that provide a valuable tool enabling researchers and consumers to accurately estimate the collection efficiency (by particle size) of a filter or EAC with a given MERV rating and determine whether its likely performance will justify its increased cost and pressure drop. Unfortunately, due to a combination of a limited test matrix and some filters that did not perform as anticipated, data for filters performing at MERV ratings of 9, 11, 13, and 15 were not acquired. Therefore, future efforts should be performed to capture data for these MERV ratings. In addition, acquiring additional data for filters with MERV ratings of 5 and 10 is desirable, as only one filter was available at that performance rating in the current study.

Also, it was observed during this study that a number of filters did not perform in accordance with the MERV ratings provided by the filter vendors. Although in many cases, the performance was only a few percentage points below the vendor-provided rating, in some cases, the performance was three or four MERV ratings below. The standard for establishing MERV ratings (ANSI/ASHRAE 52.2-1999) does not currently provide any guidance as to the number of samples of a filter type that should be tested to ensure that the manufacturer-reported MERV rating provides a statistically reasonable representation of their performance. Therefore, currently, an evaluation of a single filter could be used to characterize the performance of a very large number of filters. A study investigating the consistency of performance for filters at a given MERV rating is recommended to enable consumers to make better-informed decisions about the likely performance of purchased filters.

In this study, EACs appeared to be an excellent choice for residential air cleaning, as they provided substantially higher collection efficiencies than are available from residential filters at a fraction of the pressure drop. Evaluations of their performance to better define the likely frequency of cleaning and the collection efficiency performance as a function of the number of cleaning cycles are needed to compare the long-term operational costs of EACs to that of air filters.

The results from this study indicated that the conditioning procedures for electrostatic filters described in Addendum C of ANSI/ASHRAE 52.2-1999 warrant additional investigation. Although the results from aging and conditioning via Addendum C demonstrated similar trends for residential electrostatic filters, the results from the commercial filters contrasted strongly.

Similarly, the silicon vapor exposure conditioning method that was investigated for EACs would benefit from additional study. For two of the three units evaluated, the results between the aging and conditioning methodology showed very good agreement, however, for the third unit, the results contrasted significantly. While these results seem promising for the silicon vapor exposure method, additional study and refinement may be warranted.

For the inert particles, size measurements were made using a light-scattering technique (0.3 to 10 μm) and a technique based on electrical mobility (0.03 to 0.3 μm). In general, the collection efficiency measured at the lowest size bin for the larger range (0.35 μm midpoint) was within 10% of the highest size bin of the smaller size range (0.294 μm midpoint). Often, the agreement was much closer. However, to our knowledge a study to assess the agreement between the two measurement methods in a range of overlapping particle sizes has not been performed. It is recommended that research be performed to investigate the differences between these different measurement techniques in the overlapping size range.

1.0 Introduction

Concerns persist that buildings are vulnerable to terrorist attack using biological agents. The most serious effects of such an attack are on the health of the occupants of the buildings. Building occupants may suffer health effects ranging from irritation to severe sickness to death. The attack may also have long-term economic and other impacts due to contamination of the building. Several organizations, for example, the Army Corps of Engineers, ASHRAE, and CDC, have recognized this terrorist threat and have issued guidance documents on how to deal with it. These documents, while useful, all suffer from the fact that the scientific, engineering, and economic information needed to determine optimum courses of action is inadequate. Tools and technologies to implement optimum courses of action is often not available, are too expensive to use, or are inadequate.

The work described in this document was conducted to develop performance information (pressure drop and collection efficiency for biological and non-biological aerosols) on a wide range of commonly used ventilation filters and on three commercially available EACs that could be used in HVAC systems. For both types of aerosol reduction technologies, tests were performed with both "off-the-shelf" units and with units aged in a typical or simulated use environment to allow a better understanding of how the units would likely perform over their entire service life. In addition, testing was performed on a select subset of units using a bioaerosol to demonstrate the similarity in performance with inert particles. Empirical equations were then developed that relate particle collection efficiency to particle physical diameter over the range of 0.03 to 10 µm, which can be incorporated into indoor air quality models. (It should be noted that the publicly available performance data for filters and EACs have been typically reported for particles between 0.3 and 10 µm. However, it has recently [within the past three to four years] become feasible to economically measure the performance of air cleaning devices for particles between 0.03 and 0.3 µm. Therefore, efforts were focused on testing a wide variety of air cleaning devices over the entire 0.03 to 10 µm particle diameter range, so that empirical equations could be developed over that entire range, rather than just the 0.3 to 10 µm generally available in the literature. It should also be noted that the objective of this effort was not to determine the "typical" performance to be expected of a particular make and model of filter, nor to determine the accuracy of the MERV ratings supplied by manufacturers. Although some observations were made in regard to these two issues, they were not the objectives of this effort.)

The research described in this report consisted of four phases. In the first phase, representative HVAC air cleaning devices were selected for experimental evaluation. In the second phase, a pair of Test/QA Project Plans (QAPP) were drafted that clearly defined the test methods and procedures that were used during testing (Battelle, 2005a; Battelle, 2005b). The test protocols were primarily based on a commonly used standard, ANSI/ASHRAE Standard 52.2-1999 (ANSI/ASHRAE, 1999). This standard describes a test fixture and methodology for measuring the pressure drop and collection efficiency of ventilation filters, as well as a method for determining the MERV rating. In the third phase, the 27 commonly used air cleaning devices identified in Phase 1 were acquired and evaluated for their pressure drop and collection efficiency, as received. In addition, eight electrostatic filters were subsequently loaded with a submicrometer inert aerosol and their collection efficiency reevaluated. Ten of the devices (seven filters and three EACs) were evaluated for their collection efficiency after approximately 1 or 2 weeks, 2 or 4 weeks, 6 or 8 weeks, and 12 or 16 weeks of normal use. A separate set of ten devices (seven filters and three EACs, also known as electrostatic precipitators) were evaluated for their efficiency for a bioaerosol. Finally, three EACs were evaluated both before and after exposure to silicon vapor to simulate an actual use environment. In the fourth phase, empirical equations that related particle collection efficiency to particle physical diameter over the range of 0.03 to 10 µm were developed to fit the data collected during Phase 3. Each of these phases is described in the rest of this report.

The results of the experimental efforts described in this report will help to mitigate the impacts of a terrorist attack with a biological threat agent by:

- Providing empirical performance equations of particulate collection efficiency that can be used in indoor air quality modeling efforts to assess the impact of HVAC particulate control devices (used in residential or commercial buildings) on reducing the effects and spread of aerosol contaminants.
- Providing empirical performance data regarding the pressure drop of these air cleaning devices that can be used to assess energy requirements of air cleaners during building operation.
- Comparing the penetration of inert and biological particles through said air cleaning devices.
- Expanding the data set regarding aerosol penetration over a wider range of particle sizes.

2.0
AIR CLEANER DEVICE SELECTION

2.1 Filter Selection

The first step in the overall effort was to select the air cleaning devices for testing. Table 2-1 illustrates the recommendations provided in the statement of work for the filter test matrix. As shown in Table 2-1, the recommendations indicated that it was desired to evaluate only a few filters of moderate efficiency (MERV 5–10) so that a clear comparison between those filters and filters with greater efficiencies (charged filters and those with MERVs greater than 10) could be made. The recommendations also indicated that more attention should be focused on commercial HVAC than on residential HVAC filters. It was preferred that the filters selected for the biological and in-use tests be a subset of those selected for the inert aerosol tests so that comparisons among the various results could be made.

Table 2-2 provides a listing of the approximate U.S. market share for a variety of filter manufacturers in both the residential and commercial markets (McIlvane, 2002). As shown in Table 2-2, American Air Filter clearly holds a dominant portion of the U.S. air filter market, possessing almost a third of the residential market, and is the only company to possess more than 10% of all the different filter categories. Other manufacturers that hold significant shares of the residential market include Flanders, Purolator, and 3M. The commercial market is spread much more evenly among a larger number of companies, notably American Air Filter, Farr, Airguard, and Flanders.

Table 2-1. Test Matrix for Filter Evaluation

MERV Range	Inert Aerosol Tests	In-Use Tests	Biological Tests
Residential Filters			
5 to 10 inclusive	2[a]	0	1
11 and higher	3	0	1
Charged filter media	3	2	2
Total	8	2	4
Commercial HVAC Filters			
5 to 10 inclusive	2	0	0
11 to 12 inclusive	3	0	0
13 to 15 inclusive	3	1	1
16	3	1	1
HEPA or other >16	3	1	2
Charged filter media	3	2	2
Total	17	5	6

[a] The total number of test filters with MERV ratings less than or equal to 10 should not exceed 4.

Table 2-2. Approximate Shares of the U.S. Air Filter Market (McIlvaine, 2002)

Company	MERV 1–4 (%)	MERV 5–9 (%)	MERV 10–16+ (%)	Total (%)	Residential (%)	Commercial (%)
American Air Filter	25	12	13	16	32	12
Farr	3	9	6	7		11
Air Guard	3	9	6	7		11
Flanders	18	4	13	10	15	8
McLeod Russel		4		2		4
Purolator	8	4	3	5	10	5
Glas Floss		4		2		4
Koch		3		2		4
Freudenberg		2		1		
Air Kontrol	3	2		2	4	2
Donaldson		10	16	8		
3M		7		4	11	2
Web Products		2		1	3	<1
Camfil			5	<1		
Tridim	3	3	3	3	2	4
Hefco			4	<1		
Hepa			6	<1		
TDC		<1		<1		
Pneumafil		<1		<1		
Fleetguard			6	1		
W.L. Gore			6	1		
General Filters Inc.		1		<1	2	<1
Columbus	2	4	2	3	1	3
Dollinger		2		1		1
Filtration Group	<1	3	1	2	<1	2
BHA	<1	<1	<1	<1		<1
Trion		2		1		
Viskon-Aire		1		<1		<1
Fiberbond		2		1		2
Others	34	9	9	17	19	21

The selection of residential filters to be tested was based on the manufacturer's share of the residential market, previous experience with filter evaluations, information available on the Web sites of various vendors, an informal survey of filters available at retailers such as Home Depot, Lowe's, and Wal-Mart, and telephone conversations with various sales representatives. Approximately ten company Web sites were thoroughly examined, and various vendors were contacted to determine which of their particular air filters were the most popular, and to obtain technical information. All of the selected filters were commercially available across the United States.

From the compiled information, it was apparent that in the residential market, the most inexpensive filters dominate. These include fiberglass, disposable polyester/cotton blends, and pleated air filters. The lowest MERV-rated filter identified was 4, and the highest rated filter available in the residential market was 12. Electrostatic filters were found to dominate the medium- and high-efficiency residential filter market. No commercially available non-electrostatic residential filters with MERV ratings above 10 were identified.

Table 2-3. Evaluated Residential Filters

Required MERV Ratings (from SOW)	Identifier for Charts and Tables	Description	Manufacturer MERV Rating	Dimensions (inches)	Electrostatic	As-Is Tests	In-Use Tests	Biological Tests
5 to 10 inclusive	IPP-6-1	Pleated polyester and cotton blend	6	16 x 25 x 1	No	Yes	No	No
	2NS-8-1	Pleated polyester and cotton blend	8	16 x 25 x 1	No	Yes	No	Yes
11 and higher	3PAF-11-1	Pleasted hydrophobic synthetic media	11	16 x 25 x 2	Yes	Yes	No	No
	4FUA-12-1	Pleated polypropylene and polyolefin	12	16 x 25 x 1	Yes	Yes	No	Yes
	5RM-11-1	Pleated electrostatic	11	16 x 25 x 1	Yes	Yes	No	No
Charged Filter Media	6DDUE-8	Pleated electrostatic	8	16 x 25 x 1	Yes	Yes	Yes	Yes
	7AST-8-3	Pleated electrostatic	8	16 x 25 x 1	Yes	Yes	No	No
	8NM-10	Pleated electrostatic	10	16 x 25 x 1	Yes	Yes	Yes	Yes

As shown in Table 2-3, the manufacturer-supplied MERV ratings for the tested residential filters ranged from 6 to 12. Since the residential market was so dominated by electrostatic materials (mostly polypropylene and/or polyolefin), six filters with charged media (rather than the three specified in the statement of work [SOW]) were evaluated. An option which was discussed but not pursued was to evaluate two washable filters, which are fairly common in the market but generally have low MERV ratings. All of the tested residential filters had a recommended service lifetime of three months.

The selection of commercial filters to be tested was also based on the manufacturer's share of the residential market, previous experience with filter evaluations, information available on the Web sites of various vendors, and telephone conversations with various sales representatives. Approximately 15 company Web sites were thoroughly examined, and various vendors were contacted to determine which of their particular air filters were the most popular, and to obtain technical information. In addition, an HVAC maintenance specialist recommended different types of commercial air filters. This specialist stated that the bag or box designs performed better and had longer lifetimes than pleated or panel type filters, so two bag filters and three box filters were included in the recommended test matrix. All of the selected filters were commercially available across the United States.

As shown in Table 2-4, a much wider variety of filter types and MERV ratings are available in the commercial market. It was not difficult to find commercial filters with MERV ratings between 1 and 15. MERV 16 filters were more difficult to find, but three suitable candidates were identified with a reasonable amount of effort. As high efficiency particulate air (HEPA) filters are highly regulated, are not meant to be evaluated by ASHRAE 52.2-1999 (ASHRAE 52.2-1999), and are generally unsuitable for general HVAC usage due to their pressure drop, it was recommended that fewer HEPA filters be tested than was recommended in the SOW (Table 2-1). Instead, two additional filters with MERV ratings between 13 and 15 were added to the matrix. As shown in Table 2-4, the MERV ratings for the filters recommended for testing ranged from 7 to 16.

It may be important to note that during procurement of the commercial filters, a fairly high number of difficulties were experienced. Although some mistakes should be expected given the significant number of filters and filter types that were procured, difficulties in obtaining serviceable filters of the correct model and size were experienced with nearly one-third of the procured test filters. These difficulties included shipment of incorrect (but similar) models, incorrect sizes, incorrect frame types and materials, and damaged or improperly constructed filters. For consumers concerned with filter performance, care must be taken to inspect filters before use to ensure that the filters are appropriate for use. Much less difficulty was encountered with the procurement of the residential filters.

Table 2-4. Evaluated Commercial Filters

Required MERV Rating (From SOW)	Identifier for Charts and Tables	Description	Manufacturer MERV Rating	Dimensions (inches)	Electrostatic	As-Is Tests	In-Use Tests	Biological Tests
5 to 10 inclusive	C1APP-7	Pleated uncharged novel media prefilter	7	24 x 24 x 2	No	Yes	No	No
	C2T90-8	Panel uncharged polyester prefilter with a light tack	8	24 x 24 x 2	No	Yes	No	No
11 to 12 inclusive	C3AV-11	Pleated microfiberglass box filter	11	24 x 24 x 4	No	Yes	No	No
	C4FPC-11	Pleated microfiberglass	11[B]	24 x 24 x 12	No	Yes	No	No
	C5PSC-11	Pleated microfiberglass	13[B]	24 x 24 x 12	No	Yes	No	No
13 to 15 inclusive	C6ADP-15	Fiberglass bag filter (6 pockets)	14[B]	24 x 24 x 10	No	Yes	No	No
	C7CFER-13	Pleated synthetic box filter	14	24 x 24 x 12	Yes	Yes	No	No
	C8GZ-13	Pleated synthetic box filter	13	24 x 24 x 12	Yes[A]	Yes	Yes	No
	C14PCS	Pleated microfiberglass	14[B]	24 x 24 x 12	No	Yes	Yes	No
	C10CFS-14	Meltblown synthetic bag filter (8 pockets)	14	24 x 24 x 15	Yes	Yes	No	No
16	C11GM-16	Pleated microfiberglass	16	24 x 24 x 12	No	Yes	Yes	Yes
	C12AB-16	Pleated microfiberglass	16	24 x 24 x 12	No	Yes	No	No
	C13AMG-16	Pleated microfiberglass	16	24 x 24 x 12	No	Yes	No	No
HEPA or other > 16	C114FA-H	Pleated microfiberglass	HEPA	24 x 24 x 12	No	Yes	No	No
Charged Filter Media	C15AAA-11	Pleated electrostatic prefilte	11	24 x 24 x 2	Yes	Yes	Yes	Yes
	C16ADP-8[A]	Pleated electrostatic prefilter	8	24 x 24 x 2	Yes	No[A]	No	No
	C17FPP-8	Pleated electrostatic prefilter	8	24 x 24 x 2	Yes	Yes	Yes	Yes

[A] – Ultimately, filter C16ADP-8 was not evaluated, as commercial filter C8GZ-13-1 underwent an additional evaluation instead.
[B] – MERV rating based on Table E-1 in ASHRAE 52.2-1999

2.2 Electronic Air Cleaner Selection

EACs are a commercially available alternative to filters for residential air cleaning. Generally, EACs are marketed as possessing higher efficiencies than residential filters, lower pressure drops, and no need for frequent filter replacement. Figure 2-1 illustrates how air is purified by an electronic air cleaner. As dirty air is drawn into the unit, the particles pass through an electrostatic field and receive an ionized charge. The charged particles are then collected on alternatively charged or grounded collection plates. Frequently, an after- or post-filter is also marketed to remove odors and/or to improve the overall efficiency of the unit. Both the collection plates and the ionizing system require cleaning every 1 to 6 months. Both are typically removable for easy cleaning. The prefilters are typically made of an aluminum mesh and capture only very large dust particles.

The most common EAC sizes are 16" x 25" and 20" x 25" and typically cost between $500 to $800 installed. Residential EACs are typically designed for installation directly in the HVAC duct as "whole-house" cleaners. Portable units are also available for single-room purification (typically referred to as room air cleaners). Commercial EACs are commonly designed for wall or ceiling mounting. The wall/ceiling mounted units are typically designed to treat the air in a single room independently from the HVAC system.

Table 2-5 illustrates the recommendations that were provided in the SOW for the electronic air cleaner test matrix. As with the filter tests, the same EACs (make and model) were subjected to the inert aerosol tests, the in-use tests, and the biological tests so that direct comparisons could be made.

Similar to filter selection, the selection of EACs to be tested was based on the manufacturer's share of the market, information available on the Web sites of various vendors, and telephone conversations with various sales representatives. Approximately ten company Web sites were thoroughly examined, and various vendors were contacted to determine which of their EACs were the most popular, and to obtain technical information. Five domestic EAC manufacturers were identified: United Air Specialists, Trion, Honeywell, Skuttle, and Emerson Climate Technologies.

According to McIlvaine (2002), two companies stand out in the field of EACs. Trion is a leader in both the residential and commercial markets, whereas United Air Specialists is a leader in the commercial market. Trion has reported annual sales of $65 million, of which 23% is attributed to residential EACs and 37% comprises commercial EAC sales. Present sales are estimated at $44 million for United Air Specialists, a division of Clarcor. Nearly 100% of United Air Specialists revenue is from the sale of commercial EACs.

From the information acquired, it was clear that the residential market greatly dominates the commercial market for duct-mounted EACs. Only one duct-mounted unit was identified that was marketed to the commercial market, and that unit was marketed for both commercial and residential use. EACs designed for the commercial market are nearly exclusively wall- or ceiling-mounted units. In contrast to the commercial market, it was estimated that approximately 10% of new homes have duct-mounted EACs (McIlvaine, 2002).

Since it was desired to select EACs that were as representative as possible of the overall market, the three residential EAC units listed in Table 2-6 were selected for evaluation. All three are duct-mounted units that are available nationwide.

Figure 2-1. EAC Air Filtration Mechanism

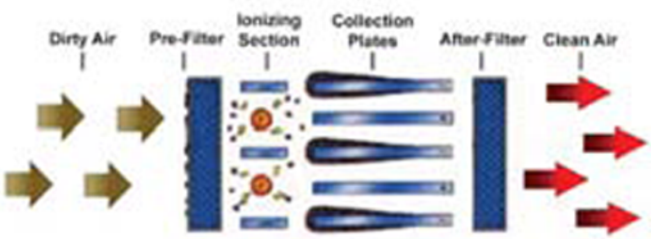


Table 2-5. Recommended Test Matrix for Electronic Air Cleaner Evaluations from the Statement of Work

EAC Tests	Inert Aerosol Tests[A]	In-Use Tests	Biological Tests
1 unit from 3 vendors	3	3	3

[A] – Including silicon vapor exposure tests

Table 2-6. Evaluated Electronic Air Cleaners

Identifier for Charts and Tables	Price ($)	Dimensions (inches)	Capacity (CFM)	Manufacturer-Provided Pressure Drop	Manufacturer-Provided Collection Efficiency
A	$405	16 x 25	Up to 2,000	0.17" w.g. at 500 fpm	> 94% at 0.35 µm (MERV 15)
H	$283	20 x 20	Up to 1,400	0.06" w.g. at 295 fpm	Up to MERV 12 at 492 fpm
P	$310	20 x 20	Up to 1,400	0.11" w.g. at 500 fpm	NA

NA = Not available

3.0
Experimental Methods

As described in Section 1.0, a variety of different test methods were used during this study. For all 24 filters and all 3 EACs, inert aerosol evaluations were performed to measure their “off-the-shelf” collection efficiency for particles with diameters between 0.03 and 10 µm. For a select group of seven filters and three EACs, testing using a bioaerosol was performed for comparison to the inert aerosol results. For a select group of seven filters and three EACs, aging was performed in conjunction with inert aerosol testing to examine the effect of use on the collection efficiency and pressure drop of the units. For a select group of eight electrostatic filters, inert aerosol testing was performed in conjunction with submicron particle conditioning in the ASHRAE 52.2-1999 test rig to evaluate the degradation in performance likely to occur with use. For all three EACs, inert aerosol testing was performed both before and after exposure to silicon vapor to simulate the degradation in performance likely to occur during actual use. Filters were selected for the bioaerosol and electrostatic tests using the recommendations listed in Table 2-1 to ensure that a variety of residential and commercial filters and a variety of MERV ratings were examined. Descriptions of the various test methods used during these evaluations are provided in turn below.

3.1 Inert Aerosol Tests

The purpose of the inert aerosol tests was to characterize the filtration efficiency of the air cleaners for particles between 0.03 and 10 µm at the maximum flow rate the units would likely encounter in actual use. The pressure drops of the units were also evaluated at 50%, 75%, 100%, and 125% of the maximum flow rates that the units would likely encounter in actual use. All testing was performed in accordance with ANSI/ASHRAE Standard 52.2-1999 “Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size” (ANSI/ASHRAE, 1999). All of the inert aerosol tests were performed by Intertek ETL Semko in their certified ASHRAE 52.2-1999 test facility. A detailed description of the facility and test procedures required for ASHRAE 52.2-1999 testing can be found in the standard (ANSI/ASHRAE, 1999) and therefore is not repeated in this document. However, for the convenience of the reader, brief summaries of the facility and procedures are provided below.

3.1.1 Inert Aerosol Test Method

All of the inert aerosol tests were conducted in Intertek ETL Semko’s certified ASHRAE 52.2-1999 test rig. The test rig’s fully enclosed ducting is primarily composed of 24” x 24” (0.61 x 0.61 m) cross section. The system operates at positive pressure to minimize infiltration and has two pleated 24” x 24” (0.61 x 0.61 m) prefilters and two 24” x 24” (0.61 x 0.61 m) HEPA filters both downstream and upstream of the blower to ensure a consistent aerosol challenge to the test air cleaner.

As required by ASHRAE 52.2-1999 (ANSI/ASHRAE, 1999), to mix the test aerosol with the air stream, an orifice plate and mixing baffle are located immediately downstream of the aerosol injection point and upstream of the test device. An identical orifice plate and mixing baffle are located after the 180 degree bend. The latter downstream orifice straightens out the flow after going around the bend and mixes the aerosol that penetrates the air cleaner. This mixing is necessary to obtain a representative downstream aerosol measurement.

Two particle sizing and counting instruments were used for the inert aerosol tests: a Climet model 500 Spectrometer OPC covering the particle diameter size range from 0.3 to 10 µm in 12 particle sizing channels and a TSI SMPS covering the range from 0.03 to 0.3 µm (shown in Figure 3-1). The OPC uses a laser-light illumination source and has a wide collection angle for the scattered light. The SMPS consisted of a TSI Model 3080L electrostatic classifier and a TSI Model 3022A-S condensation particle counter. It should be recognized that the two selected instruments measure particles based upon different physical properties: electrical mobility in the case of the SMPS and light scattering in the case of the OPC. It is well understood in the field of particle physics that these two size measurements are not directly comparable. This did not affect the efficiency measurements for specific particle sizes but was chiefly responsible for the minor gaps in continuity that were occasionally observed between the filtration efficiency curves obtained from the two instruments.

Figure 3-1. Aerosol Sampling Instruments, TSI SMPS (left) and Climet CI-500 (right)

Two aerosol generators were used for the tests. Both used an aqueous solution of potassium chloride (KCl) to generate particles. The concentration of KCl in the solution was varied as needed to generate particles in the proper size range. For the 0.3 to 10 µm tests, an external air atomizing nozzle was used along with a KCl solution of approximately 300 g KCl to 1 liter of distilled water. For the 0.03 to 0.3 µm tests, a Collison nebulizer was used with a solution of approximately 100 g KCl to 1 liter of distilled water. Both generators were connected to a 12-inch (0.30 m) diameter, 51-inch (1.3 m) tall transparent acrylic spray tower. The tower allowed the salt particles to dry as well as the larger particles to settle out of the challenge aerosol air stream. After drying in the spray tower, the challenge aerosol passed through an aerosol neutralizer before being injected counter to the airflow in the test duct. This was necessary as aerosol particles have a tendency to collect static charge, which may influence their filtration characteristics.

As required by ASHRAE 52.2-1999 (ANSI/ASHRAE, 1999), the aerosol sampling lines (both upstream and downstream) were composed of stainless steel, used gradual bends when needed to minimize particle losses, and used changeable sampling nozzles to ensure isokinetic sampling at the various flow rates. For the 0.3 to 10 µm tests, an automated valve system was used to automatically control the upstream and downstream sampling by the OPC. For the 0.03 to 0.3 µm tests, the sampling lines were manually altered.

It should be noted that the inert aerosol tests consisted only of the pressure drop measurements and the initial collection efficiency measurements specified in ASHRAE 52.2-1999 (ANSI/ASHRAE, 1999). ASHRAE 52.2-1999 (ANSI/ASHRAE, 1999) also describes a procedure for dust loading with a standardized loading dust in conjunction with a series of collection efficiency tests to examine the collection efficiency of the air cleaners as they become loaded with dust. At the direction of the sponsor, these loading procedures were not performed.

In addition, it also should be noted that the tests of the EACs were performed by the procedures described above with only one modification. In the case of the EACs, care was taken to ensure that the devices were powered and properly operating during the tests.

3.1.2 Inert Aerosol Data Analysis

As specified in ANSI/ASHRAE Standard 52.2-1999 (ANSI/ASHRAE, 1999), the computation of inert aerosol filtration efficiency was based on the ratio of the downstream-to-upstream particle concentrations corrected on a channel-by-channel basis for:

- Background counts (i.e., upstream and downstream counts observed when the aerosol generator is off)
- The correlation ratio measured at the start of the test sequence

These data were used for determining filtration efficiency by computing the observed penetration ($P_{observed}$):

$$P_{observed} = \frac{(D - D_b)}{(U - U_b)} \qquad (1)$$

where:

D = Downstream particle count,
D_b = Downstream background count,
U = Upstream count, and
U_b = Upstream background count.

As specified in ANSI/ASHRAE Standard 52.2-1999, to remove system bias, the observed penetration was corrected by the correlation ratio (R) (the $P_{observed}$ measured during a blank control test for which no filter is installed in the duct).

$$P_{corrected} = P_{observed} \,/\, R \qquad (2)$$

The filtration efficiency was then computed as:

$$\textit{Filtration Efficiency}\ (\%) = 100\,(1 - P_{corrected}) \qquad (3)$$

Data from the inert aerosol tests were verified to ensure that all measured parameters fell within reasonable agreement with the anticipated results before continuing/terminating testing.

A sample set of calculations from the inert aerosol tests is provided in Appendix A.

3.2 Bioaerosol Tests

A select group of filters (seven) and EACs (three) were evaluated against a bioaerosol. The purpose of the bioaerosol tests was to compare the penetration of a bioaerosol to the penetration of a similarly-sized inert aerosol to determine whether there were any significant differences between the penetration of bioaerosol and inert particles.

3.2.1 Bioaerosol Test Method

The first step in the bioaerosol testing was the selection of an organism. The bioaerosol tests were conducted using the spore form of the Gram-positive bacteria *Bacillus atrophaeus* (formerly *B. subtilis var niger* and *Bacillus globigii* or BG). The BG spore is elliptically shaped with dimensions of 0.7 – 0.8 x 1 – 1.5 µm. BG spores were used for testing because they:

- Have historically been used as a surrogate for anthrax spores
- Are very durable
- Possess natural resistance to heat and desiccation
- Are significantly resistant to loss of culturability during aerosolization and collection
- Have a median aerodynamic diameter of approximately 1 µm, thus they possess a reasonably good chance of penetration through air cleaning devices
- Can be generated in sufficient concentrations for testing
- Can be generated as single spores with narrow size distributions

The BG spore challenge suspensions were prepared using a dry Dugway Proving Ground BG powder. The Dugway BG was processed post-production. The raw fermentation product was concentrated to achieve 20% solids content. The concentrated BG suspension was then spray dried. Aerosil 812 S (Degussa GmbH;

Düsseldorf, Germany) was added as the dried batches were blended. The dried BG was then jet milled and additional Aerosil 812 S was added to achieve the desired physical properties. The BG spore challenge suspensions were prepared for testing by resuspending 25 grams of the dry Dugway Proving Ground BG powder in 1000 mL sterile 18 megohm/cm water. (Resuspension in sterile 18 megohm/cm water is essential to minimize the particle counts from sources other than the organisms themselves [e.g., dissolved solids].) This stock suspension was approximately 5.0 x 10^9 (colony forming units) CFU/mL and was used to prepare the nebulization suspension for each aerosol test. The nebulization suspension for each test was prepared by diluting 20 mL of the stock suspension in 180 mL of 18 megohm/cm water, yielding a challenge concentration of approximately 5.0 x 10^8 CFU/mL.

Because the aerosol generation and measurement techniques and equipment required for bioaerosol testing were different from those required for ASHRAE 52.2-1999, and required a higher level of containment and different handling protocols, the bioaerosol testing was performed in a separate test facility from the inert aerosol testing. A diagram of the bioaerosol evaluation test duct is shown in Figure 3-2. The test duct possessed an approximately 24" x 24" cross-sectional sampling zone where an array of reference samplers and the unit being tested were exposed to the same well-mixed bioaerosol. The air was pulled through the test system by a blower located downstream of a pair of 24" x 24" x 12" HEPA filters to ensure bioaerosol containment. A pair of 24" x 24" x 12" HEPA filters were also used on the intake to the test duct to prevent any contamination of the test system by background biological materials.

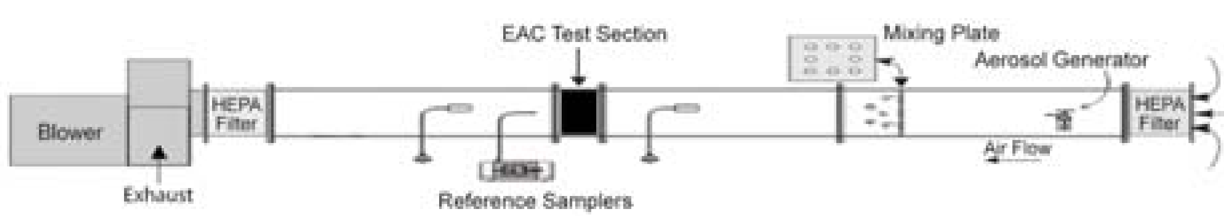
As shown in Figure 3-2, the challenge organism suspensions were aerosolized using a single 24-jet Collison nebulizer (BGI, Waltham, MA) at 40 PSI air pressure. The Collison nebulizer generated droplets with an approximate volume mean diameter of 2 µm. Since the remaining water evaporated upon exposure to the large volume of air (> 800 cfm) moving through the test system, the aerodynamic mass median diameter of the challenge aerosol was generally less than 1 µm (single spores). Upstream and downstream sampling of the aerosol was accomplished isokinetically, using nine upstream and nine downstream 47-mm water-soluble gelatin filters (18 total samples). These filters were placed in standard 47-mm filter housings and connected to the sampling probes. (Filter holders and impactors were autoclaved at 121 ºC at a pressure of approximately 19 PSI for 20 minutes and then dried with a 10-minute vacuum exposure at 10 inHg prior to testing.) A vacuum pump was used to sample through the filters at a rate of approximately 7.5 L/min. Once sampled, the filters were removed from their holders, dissolved in 10 mL of pH 7.4 phosphate-buffered saline (PBS), and then diluted to an appropriate concentration before being plated on tryptic soy agar (TSA). Each sample was plated in triplicate and incubated overnight at 32 ºC. After the incubation period, the colonies were counted using the Qcount™ automatic plate counter (Spiral Biotech, Inc.), and the colony counts were used to calculate the filtration efficiency of the test air cleaner.

The size distribution of the challenge aerosol was determined using a six-stage Battelle cascade impactor (BCI). The cutoff aerodynamic size ranges for Stage 1 to Stage 6 were 16.0 µm and greater, 16.0 – 8.0, 8.0 – 4.0, 4.0 – 2.0, 2.0 – 1.0, and 1.0 – 0.5 µm, respectively. Particles collected on the filter were smaller than 0.5 µm (the filter was considered a seventh stage). The glass impactor slides were coated with a thin film of KY Jelly®, a water-soluble adhesive. The slides were extracted in 100 mL beakers, using 10 mL of pH 7.4 PBS with shaking at 32 ºC for 10 minutes at a speed of 120 rpm. The samples were then diluted to an appropriate concentration and plated on TSA. Each sample was plated in triplicate and incubated overnight at 32 ºC. After the incubation period, the colonies were counted using the Qcount™ automatic plate counter (Spiral Biotech, Inc.), and the colony counts were used to calculate the size distribution of the bioaerosol.

The experimental conditions and sampling times were adjusted so that these samplers were used within their upper and lower sampling limits. To quantify the microbial counts, the BG samples were plated according to Battelle's standard operating procedure (SOP), ABAT-E-002-00 Standard Operating Procedure for the Operation and Maintenance of the Spiral Biotech Autoplate® 4000 Automated Spiral Plater. Post-extraction, BG samples were diluted in PBS, using serial 10-fold dilutions to achieve concentrations in the range of 20 CFU/mL to approximately 10,000 CFU/mL. Samples were then plated in triplicate on TSA using the Spiral Biotech Autoplate® 4000. This instrument deposits 50 µL of sample over the surface of the plate in a spiral pattern with a distribution that dilutes the sample, allowing the enumeration of samples in the aforementioned range. The plates were incubated overnight at 32 ºC, and CFU/mL were determined by counting the resulting colonies with the Spiral Biotech QCount® colony counter.

Both before the air cleaner tests were conducted and during each test, the uniformity of aerosol concentration was measured. Both with and without air cleaners present, bioaerosol measurements were performed both upstream and downstream of the air cleaner test location, at cross-sectional planes perpendicular to the flow. The cross-section was divided into nine equal areas, and concentration was measured at the center of each area. The mean concentration and the coefficient of variation (CV, computed as the standard deviation divided by the mean) of the nine corresponding grid point concentration values was then calculated. The maximum acceptable CV value was set at 30%.

Figure 3-2. Schematic of the Bioaerosol Test Rig



If the measured CV exceeded 30%, the airflow baffles were modified, and the test was repeated until the requirement of CV less than 30% was met. This uniformity test was performed at both flow rates used for the bioaerosol tests (820 cfm and 984 cfm).

Similarly, before each bioaerosol test, airflow rates were measured using a hot-wire anemometer to measure the air velocity at the nine points that were identified in the center of the nine equal, imaginary areas across the test duct at the inlet location of the air cleaners. The mean flow velocity was calculated by averaging the nine velocity values and multiplying the mean velocity by the cross-sectional area. The CV of the velocities was also calculated. The maximum acceptable CV value was set at 25%. If the measured CV exceeded 25%, the airflow baffles were modified, and the test was repeated until the requirement of CV less than 25% was met.

3.2.2 Bioaerosol Data Analysis

Data analysis was performed using commercially available software (Microsoft Excel) by manually entering the raw data into a spreadsheet and calculating the results from a series of equations. Samples were collected simultaneously using multiple samplers.

The mean upstream and downstream concentrations were calculated as:

$$\overline{U} = \frac{\sum_{i-1}^{n} Ui}{n} \quad \text{and} \quad \overline{D} = \frac{\sum_{i-1}^{n} Di}{n} \qquad (4)$$

where:

D_i = Downstream concentration of the ith sample and n is the number of samples collected,

U_i = Upstream concentration of the ith sample and n is the number of samples collected,

$\overline{D}$ = Mean downstream concentration with a unit installed in the test rig, and

$\overline{U}$ = Mean upstream concentration with a unit installed in the test rig.

The calculation of the penetration was based on the ratio of the downstream to upstream culturable concentrations. The penetration with the unit installed in the test rig ($P_{measured}$) is shown in the following equation:

$$P_{measured} = \overline{D} / \overline{U} \qquad (5)$$

where:

$P_{measured}$ = Penetration with the unit installed in the test rig.

The P_{100} (no unit installed in the test rig) was calculated as the $P_{measured}$ but using the results of the no-filter tests.

$$P_{100} = \overline{D_{100}} / \overline{U_{100}} \qquad (6)$$

where:

$\overline{D}_{100}$ = Mean downstream concentration with no unit in the test rig and

$\overline{U}_{100}$ = Mean upstream concentration with no unit in the test rig.

To remove system bias, the $P_{measured}$ was corrected by the penetration of a blank "no-filter" test for which no air cleaner was installed in the duct (P_{100}). (P_{100} was 0.995 for the 820 cfm tests and 1.034 for the 984 cfm tests.)

$$P_{corrected} = P_{measured} / P_{100} \qquad (7)$$

The filtration efficiency was then calculated as shown in Equation 8.

$$\textit{Filtration Efficiency } \textbf{(\%)} = 100\,(1 - P_{corrected}) \qquad (8)$$

Lastly, the combined standard deviation of the penetration measurements was calculated to indicate one standard deviation of the penetration based on the CV of the upstream and downstream culturable concentrations as shown in Equation 9.

$$\textit{Combined Standard Deviation} = P_{measured}\,[(CV_U)^2 + (CV_D)^2]^{0.5} \qquad (9)$$

Where:

$P_{measured}$ = Penetration calculated from the upstream and downstream culturable concentrations,

CV_U = Coefficient of variation from the upstream concentrations, and

CV_D = Coefficient of variation from the downstream concentrations.

A sample set of calculations from the bioaerosol tests is provided in Appendix B.

3.3 Aging of Air Cleaners for In-Use Tests

For a select group of seven filters and three EACs, aging was performed in conjunction with inert aerosol testing to examine the effect of dust loading in actual use environments on the collection efficiency and pressure drop of the units.

3.3.1 Aging of Filters

To determine the effects of dust accumulation, a select group of seven filters was tested using the inert aerosol procedures described in Section 3.1 both before and after aging in actual use environments. As shown in Tables 2-3 and 2-4, two residential filters and five commercial filters were evaluated "in-use." For all seven filters, evaluations using the procedures described in Section 3.1 were performed before use and then after approximately 2 weeks, 4 weeks, 8 weeks, and 12 (residential), or 16 (commercial) weeks of use. It is important to note that it was not feasible to use the same filter for all five of these evaluations due to the excessive amount of shipping and handling that would be required to transport the filter between the use environment and the test facility. Therefore, five identical (from the same package or lot) filters of each of the seven filter types were used during testing.

For the residential filters, aging was accomplished by using the filters in the home residences of two Battelle staff members. Because of the significant differences in the operational parameters of residential HVAC systems, electronic data logging systems were installed into each residence to record the actual hours of operation of the blower. Photographs of the residential HVAC systems used are provided in Appendix C.

For the commercial filters, aging was accomplished by insertion into two separate operational HVAC systems at Battelle's facilities in Columbus, Ohio, and West Jefferson, Ohio. Both of these HVAC systems operated using 100% fresh (outdoor) air intake, 24 hours per day, 7 days per week. Both of these systems used a pair of filters to process the outdoor air — a bank of 24" x 24" x 2" prefilters followed by a bank of 24" x 24" x 12" medium- to high-efficiency filters. Photographs of the two HVAC systems are provided in Appendix C. In both cases, a complete replacement of all the filters (both prefilters and medium/high-efficiency filters) in the entire filter bank was performed when aging was initiated. This was performed to ensure that the flow (and thus the dust loading) through the various filters would be as homogenous as possible during the entire aging process. All of the aged filters were initially inserted into the system on the same day. The filters were removed individually, when their aging duration had been completed, and replaced with a new filter of the same type. Because the maximum recommended lifetime for the residential filters was 3 months, the final aging duration was limited to 12 weeks instead of the 16 weeks that was used for the commercial filters.

After the filters were exposed, they were weighed, photographed, and placed into special carrying cases that were designed to minimize the loss of loaded dust due to vibration, shock, or damage during delivery to the test facility. The filters were weighed both before and after delivery to the test facility to ensure that the loss of loaded dust was minimal. Delivery from the aging location to the testing location was performed directly by Battelle staff to ensure that no damage occurred during transit.

All filters for this study were stored in an indoor, air-conditioned environment both prior to and after aging. Each filter was numbered using a permanent marker. All of the test filters used in this study were inspected before testing/use and were found to be free of defects such as holes or defects in the media, damage or defects in the frame, and gaps in the seals between the medium and frame. Damaged/defective filters were not used in any of the tests.

It may be important to note that significant difficulties were encountered in acquiring commercial filters for testing that did not contain minor or major defects due to a combination of manufacturing errors, damage during transit, incorrect filter models being sent, etc. Approximately one third of the commercial filters required some sort of remedial action to ensure that pristine samples of the correct filter model were acquired. In contrast, acquisition of the residential filters and EACs required no remedial action whatsoever. Therefore, to ensure that the desired performance level is met, filter purchasers should institute a standard practice of carefully inspecting each filter that is received. A careful comparison between the model numbers on the filters/boxes/purchase order should be performed to ensure that the proper filters were received. In addition, each filter should be visually inspected to ensure that the filter has the proper dimensions and gasketing; has no holes, rips, or tears in the medium; and is properly sealed (no breaks) to the filter frame. The filters should be stored in a clean, dry area away from normal foot traffic and rainwater seepage. During installation, care must be taken to ensure that the filters are not handled roughly or damaged, and that they are properly installed in the filter holders with no gaps in the filter assembly and no loose or unused clamping or sealing mechanisms. Without these procedures, it is likely that filter performance will not match the desired values.

3.3.2 Aging of Electronic Air Cleaners

To determine the effects of dust accumulation, three of the EACs were tested using the inert aerosol procedures described in Section 3.1 both before and after aging in actual use environments. For all three units, evaluations using the procedures described in Section 3.1 were performed before use and then after 1 week (168 hours), 2 weeks (336 hours), 6 weeks (1,008 hours), and 12 weeks (2,016 hours) of use. In contrast to the aged filters, the same unit was used for all five of these evaluations.

Due to the size and weight of the units and the difficulty and custom nature of installing/removing them into/from a residence, it was not feasible to age them in an actual use environment separate from the test facility. Therefore, an aging system was fabricated and operated in the test facility at Intertek ETL Semko. A photograph of the aging system is provided in Appendix D. The aging system consisted of a single blower attached to a plenum that was connected to three separate ducts. Each duct contained an air flow monitor as well as an adjustable damper. When operating, the aging system continuously (100% operation, 24 hours per day, 7 days per week) drew unconditioned air from the test facility through the EACs. The airflow monitors were periodically monitored and the dampers modified as needed to ensure that the airflow through each unit was approximately 295 fpm during the entire exposure period. Since the pressure drop of the EACs did not significantly change during loading, adjustment of the dampers was rarely necessary. Therefore, aging of all of the EACs occurred simultaneously.

All the EACs for this study were stored in an indoor, air-conditioned environment both prior to and after aging. Each unit was numbered using a permanent marker. All of the units used in this study were inspected before testing/use and were found to be free of defects such as broken ionizing wires, unattached connectors, holes or defects in the media (for the one unit that had a filter), damage or defects in the frame, and gaps in the seals between the cells and frame. (While significant difficulties were encountered in acquiring commercial filters for testing that did not contain defects, none of the EACs that were procured contained any defects.) However, care was taken to ensure that the cells in the air cleaners remained operational during both aging and testing, as it was observed during initial testing that the electrical connections on some of the cleaners could loosen during use, powering down the unit and greatly reducing the collection efficiency.

3.4 Conditioning of Electrostatic Filters

For non-electrostatic air filters, collection efficiency and pressure drop will be at a minimum prior to any loading/usage. Once usage begins, their pressure drop and collection efficiency will generally increase as particles are loaded because the loaded particles increase the resistance to airflow as well as create a more torturous path for particles to pass through. However, electrostatic filters achieve a relatively high collection efficiency at relatively low pressure drops by relying heavily on the electrostatic attraction of particles to their charged media. It is well known that the collection efficiency of electrostatic filters generally decreases after being loaded with a small amount of dust. Similar to other filters, eventually, the collection efficiency of electrostatic filters generally increases with dust loading once a substantial dust cake starts to build up on the filter. Therefore, the minimum collection efficiency for electrostatic filters generally is not at initial use, but at some point between initial loading before a substantial dust cake has built up.

Therefore, eight electrostatic filters were evaluated using a modified inert aerosol test method (Section 3.1) that involved conditioning to identify their minimum collection efficiency, rather than their initial collection efficiency. This modified inert aerosol test method was performed in accordance with the latest recommendation from ASHRAE, namely draft Addendum C for ANSI/ASHRAE Standard 52.2-1999.

Essentially, this test method consisted of multiple performances of the procedures described in Section 3.1. Their collection efficiencies and pressure drops were initially measured using the methods described in Section 3.1. Following the initial collection efficiency tests, the filters were loaded in the ASHRAE 52.2-1999 test rig with submicron potassium chloride particles until the CT (concentration*time) of the filters was on the order of $3.2*10^7$ (particles*min)/cm^3. The collection efficiency of the filters was again measured in both the 0.03 to 0.3 and 0.3 to 10 µm particle diameter ranges, using the methods described in Section 3.1. Loading of the filters with additional potassium chloride particles was again performed until the CT had approximately doubled (approximately $7*10^7$ [particles*min]/cm^3). The collection efficiency of the filters was again measured in both the 0.03 to 0.3 and 0.3 to 10 µm particle diameter ranges. This pattern was repeated until the collection efficiency of the filter did not degrade (decrease by more than 2% in more than one individual size bin between 0.3 and 10 µm) between two successive loadings or when the CT reached $1.2*10^9$ (particles*min)/cm^3. As explained in draft Addendum C of ASHRAE 52.2-1999, the purpose of these loading tests is to determine the minimum collection efficiency of electrostatic filters, which are known to initially degrade in collection efficiency with use until the built-up dust cake begins to compensate for the loss of available electrostatic charge on the filter fibers. (Based on previous testing [Hanley and Owen, 2003], a CT of $3.1*10^8$ [particles*min]/cm^3 is thought to represent approximately 3 months of full-time use.)

3.5 Conditioning of Electronic Air Cleaners Using Silicon Vapor

In addition to the "in-use" tests described in Section 3.3, three EACs were evaluated by the inert aerosol methods described in Section 3.1 both before and after exposure to silicon vapor. The purpose of the exposure to silicon vapor was to compare the results from exposure to silicon vapor to the results from the "in-use" tests to determine whether the silicon vapor exposure resulted in a realistic assessment of their likely performance after one month of actual use. The silicon vapor exposure was performed using the draft protocol from the EPA ETV program (Hanley et al., 2002). The EAC cell (or cells) were placed in a small (16 to 24 ft^3) chamber equipped with a 12" nominal diameter fan. The fan moved air over a small holding pan filled with DOW Corning 244 fluid (octamethylcyclotetrasiloxane) and through the EAC cell(s). The cell(s) were placed in the chamber and energized according to their normal operating voltage. The mixing fan was operated for 3 hours with the cells off and the chamber sealed; then the cells were powered for 8 hours. The cells were then powered down, the chamber vented, and the cells removed. The cell(s) were replaced in the EAC and the collection efficiency measured as described in Section 3.1. Based on limited previous testing (Hanley et al., 2002), 8 hours of exposure to the silicon vapor approximates one month of full time usage. (This conditioning method duration approximation is based on testing of one electronic air cleaner in a single home over several months [Hanley et al., 2002].)

4.0 Test Results

As described in Section 3, a variety of different test methods were used during this study. For both the filters and EACs, inert aerosol evaluations were performed to measure their collection efficiency for particles with diameters between 0.03 and 10 µm. For a select group of both filters (seven) and EACs (three), testing using a bioaerosol was performed for comparison to the inert aerosol results. For a select group of both filters (seven) and EACs (three), aging was performed in conjunction with inert aerosol testing to examine the effect of use on the collection efficiency and pressure drop of the units. For a select group of electrostatic filters (eight), inert aerosol testing was performed in conjunction with conditioning in the ASHRAE 52.2-1999 test rig to evaluate the degradation in performance likely to occur with use. For a select group of the EACs (three), inert aerosol testing was performed both before and after exposure to silicon vapor to simulate the degradation in performance likely to occur during actual use. Descriptions of the results from these tests are provided in turn below.

The results discussed in Section 4.1 include results only from tests of air cleaners in their original "off-the-shelf" condition. Section 4.2 contains the measured bioaerosol penetration efficiencies for a selected subset of seven unaged filters and three EACs. Results after the various aging and conditioning steps are discussed in Sections 4.3 and 4.4, respectively. A complete listing of the results from the evaluations of each "off-the-shelf" air cleaner is provided in Appendix E. A summary of the results is provided for the filters and EACs in the following sections.

4.1 Unaged – "Off-the-Shelf" Inert Aerosol Evaluations

The purpose of the inert aerosol tests was to characterize the filtration efficiency of the air cleaners for particles between 0.03 and 10 µm at the maximum flow rate the units would likely encounter in actual use. The pressure drops of the units were also evaluated at 50%, 75%, 100%, and 125% of the maximum flow rates that the units would likely encounter in actual use. A total of 27 different air cleaning devices (24 filters, 3 EACs) were evaluated in this manner in their "as-received" or "off-the-shelf" condition.

4.1.1 Unaged Filters

Tables 4-1 and 4-2 summarize the results from the "off-the-shelf" evaluations of the residential and commercial filters, respectively. As shown in these tables, the measured pressure drops of the filters generally corresponded quite well (± 30%) with the information provided by the various manufacturers, although in a few cases, the measured pressure drops were somewhat greater. In terms of collection efficiency, the MERV ratings that were determined from the tests ranged from two ratings above to four ratings below the manufacturer's nominal MERV rating. It should be noted that the testing performed on the current study did not include the dust-loading portion of ANSI/ASHRAE 52.2-1999; therefore, the MERV ratings were determined from the initial collection efficiency portion of the test only. As noted in Tables 4-1 and 4-2, some manufacturers did not provide MERV ratings so MERV ratings were estimated based on the literature provided by the manufacturer and Table E-1 from ANSI/ASHRAE 52.2-1999 (1999). Lastly, it should be noted that the testing during this study consisted of evaluations of single filters, so the results may not be representative of typical performance. (ANSI/ASHRAE 52.2-1999 does not provide any guidance as to the number of samples of a filter type that should be tested to provide a statistically reasonable representation of their typical performance.) It should be noted that the purpose of this study was not to evaluate manufacturer-provided MERV ratings. The results listed in Tables 4-1 and 4-2 are provided to illustrate that the obtained results were reasonably similar to the anticipated performance based on the obtained literature. Since some variation should be expected in individual filters, some number of replicates would have been needed to make these comparisons statistically meaningful.

Figures 4-1 through 4-18 graphically illustrate the collection efficiencies and pressure drops that were measured for the "off-the-shelf" filters. The results from the measurements were compiled onto the various charts according to the MERV ratings that were obtained. As shown in Figures 4-1 through 4-18, except for the MERV 8 filters shown in Figure 4-7, the collection efficiency curves obtained for the filters with identical MERV ratings were similar in shape. In addition, collection efficiencies measured with the OPC (0.3 to 10 µm) generally corresponded very well with the collection efficiencies measured with the SMPS (0.03 to 0.3 µm), in the common region of overlap around 0.3 µm, with only a few discontinuities.

Table 4-1. Results from the Inert Aerosol Evaluations of "Off-the-Shelf" Residential Filters

Required MERV Ratings (from SOW)	Identifier for Charts and Tables	Description	Electrostatic	MERV Rating (literature)	MERV Rating (testing)	MERV Efficiencies (%) E1 – 0.3 – 1.0 µm E2 – 1.0 – 3.0 µm E3 – 3.0 – 10 µm	Literature Pressure Drop (in. w.g.)	Measured Pressure Drop (in. w.g.)	Notes
5 to 10 inclusive	IPP-6-1	Pleated polyester and cotton blend	No	6	5	E1= 5.8 E2= 33.0 E3= 33.3	0.18 at 819 cfm	0.18 at 833 cfm	MERV 6 requires E3 > 35%
	2NS-8-1	Pleated polyester and cotton blend	No	8	6	E1= 5.9 E2= 15.7 E3= 41.3	NA	0.19 at 820 cfm	MERV 7 requires E3 > 50%
11 and higher	3PAF-11-1	Pleasted hydrophobic synthetic media	Yes	11	8	E1= 23.3 E2= 37.9 E3= 82.1	0.2 at 850 cfm	0.18 at 820 cfm	MERV 9 requires E3 > 85%. Reported dust spot efficiency matches MERV 9.
	4FUA-12-1	Pleated polypropylene and polyolefin	Yes	12	12	E1= 39.7 E2= 80.8 E3= 92.1	NA	0.09 at 820 cfm	None
	5RM-11-1	Pleated electrostatic	Yes	11	7	E1= 19.2 E2= 64.9 E3= 68.7	0.12 at 694 cfm	0.25 at 820 cfm	MERV 8 requires E3 > 70%
Charged Filter Media	6DDUE-8	Pleated electrostatic	Yes	8	7	E1= 20.6 E2= 51.9 E3= 56.8	0.17 at 820 cfm	0.14 at 820 cfm	MERV 8 requires E3 > 70%
	7AST-8-3	Pleated electrostatic	Yes	8	7	E1= 19.0 E2= 62.6 E3= 61.3	NA	0.29 at 820 cfm	MERV 8 requires E3 > 70%
	8NM-10	Pleated electrostatic	Yes	10	12	E1= 31.2 E2= 82.4 E3= 91.4	NA	0.43 at 820 cfm	High pressure drop

NA – Not available

Table 4-2. Results from the Inert Aerosol Evaluations of "Off-the-Shelf" Commercial Filters

Required MERV Rating (From SOW)	Identifier for Charts and Tables	Description	Electrostatic	MERV Rating (literature)	MERV Rating (testing)	MERV Efficiencies (%) E1 – 0.3 – 1.0 µm E2 – 1.0 – 3.0 µm E3 – 3.0 – 10 µm	Literature Pressure Drop (in. w.g.)	Measured Pressure Drop (in. w.g.)	Notes
5 to 10 inclusive	C1APP-7	Pleated uncharged novel media prefilter	No	7	6	E1= 4.4 E2= 24.3 E3= 49.7	0.28 at 2,000 cfm	0.28 at 1,968 cfm	MERV 7 requires E3 > 50%
	C2T90-8	Panel uncharged polyester prefilter with a light tack	No	8	7	E1= 15.0 E2= 44.9 E3= 51.4	0.50 at 2,000 cfm	0.41 at 1,968 cfm	MERV 8 requires E3 > 70%
11 to 12 inclusive	C3AV-11	Pleated microfiberglass box filter	No	11	10	E1= 34.3 E2= 61.5 E3= 92.5	0.45 at 2,000 cfm	0.46 at 1,968 cfm	MERV 11 requires E2 > 65%
	C4FPC-11	Pleated microfiberglass	No	11^{B}	8	E1= 25.7 E2= 43.7 E3= 78.9	0.30 at 2,000 cfm	0.36 at 1,968 cfm	MERV 9 requires E3 > 85%
	C5PSC-11	Pleated microfiberglass	No	13^{B}	12	E1= 59.8 E2= 83.6 E3= 97.2	0.60 at 2,000 cfm	0.64 at 1,968 cfm	MERV 13 requires E2 > 90%
13 to 15 inclusive	C6ADP-15	Fiberglass bag filter (6 pockets)	No	14^{B}	14	E1= 82.1 E2= 98.1 E3= 99.4	1.48 at 2,000 cfm	1.68 at 1,968 cfm	Excessive pressure drop was measured because tested filter was designed for only 1/3 of the test flow rate.
	C7CFER-13	Pleated synthetic box filter	Yes	14	14	E1= 81.1 E2= 96.8 E3= 99.8	0.58 at 2,000 cfm	0.85 at 1,968 cfm	MERV 15 requires E1 > 85%
	C8GZ-13	Pleated synthetic box filter	Yes^{A}	13	12, 14^{A}	E1= 69.4, 77.5^{A} E2= 88.3, 96.3^{A} E3= 98.6, 98.7^{A}	0.44 at 2,000 cfm	0.59, 0.63^{A} at 1,968 cfm	MERV 13 requires E2 > 90%, MERV 14 requires E1 > 75%
	C14PCS	Pleated microfiberglass	No	14^{B}	12	E1= 71.3 E2= 89.4 E3= 98.6	0.60 at 2,000 cfm	0.60 at 1,968 cfm	MERV 13 requires E2 > 90%
	C10CFS-14	Melt-blown synthetic bag filter (8 pockets)	Yes	14	14	E1= 81.0 E2= 95.0 E3= 98.9	0.50 at 2,000 cfm (for filter with 12 pockets)	0.57 at 1,968 cfm	MERV 15 requires E1 > 85%

Table 4-2. Results from the Inert Aerosol Evaluations of "Off-the-Shelf" Commercial Filters (Continued)

Required MERV Rating (From SOW)	Identifier for Charts and Tables	Description	Electrostatic	MERV Rating (literature)	MERV Rating (testing)	MERV Efficiencies (%) E1 – 0.3 – 1.0 µm E2 – 1.0 – 3.0 µm E3 – 3.0 – 10 µm	Literature Pressure Drop (in. w.g.)	Measured Pressure Drop (in. w.g.)	Notes
16	C11GM-16	Pleated microfiberglass	No	16	16	E1= 98.6 E2= 99.9 E3= 100	0.61 at 2,000 cfm	0.85 at 1,968 cfm	High-capacity unit was tested. 95% DOP filter
	C12AB-16	Pleated microfiberglass	No	16	16	E1= 98.0 E2= 99.7 E3= 99.9	0.95 at 2,000 cfm	1.01 at 1,968 cfm	95% DOP filter
	C13AMG-16	Pleated microfiberglass	No	16	16	E1= 96.4 E2= 96.8 E3= 97.5	0.95 at 1,900 cfm	1.29 at 1,968 cfm	95% DOP filter
HEPA or other > 16	C114FA-H	Pleated microfiberglass	No	HEPA	16+	E1= 100 E2= 100 E3= 100	1.45 at 2,000 cfm	1.34 at 1,968 cfm	HEPA filter
Charged Filter Media	C15AAA-11	Pleated electrostatic prefilter	Yes	11	7, 8[C]	E1= 41.1, 47.5[C] E2= 71.9, 72.9[C] E3= 66.6, 71.4[C]	0.38 at 2,000 cfm (500 fpm)	0.34 at 1,968 cfm, 0.40 at 984 cfm (492 fpm)[C]	Tested a 24" x 24" x 2" and a 12" x 24" x 2"[C]
	C16ADP-8[A]	Pleated electrostatic prefilter	Yes	8	NA	NA	NA	NA	NA
	C17FPP-8	Pleated electrostatic prefilter	Yes	8	8, 7[C]	E1= 48.3, 39.1[C] E2= 91.1, 75.5[C] E3= 81.3, 64.7[C]	0.30 at 2,000 cfm (500 fpm)	0.44 at 1,968 cfm, 0.55 at 984 cfm (492 fpm)[C]	Tested a 24" x 24" x 2" and a 12" x 24" x 2"[C]

[A] – Ultimately, filter C16ADP-8 was not evaluated, as commercial filter C8GZ-13-1 underwent an additional evaluation instead.
[B] – MERV rating based on Table E-1 in ASHRAE 52.2-1999
[C] – Tested both a 24" x 24" x 2" and a 12" x 24" x 2" filter
NA – Not available

Figure 4-1. Measured Collection Efficiencies of Unaged MERV 5 Filters

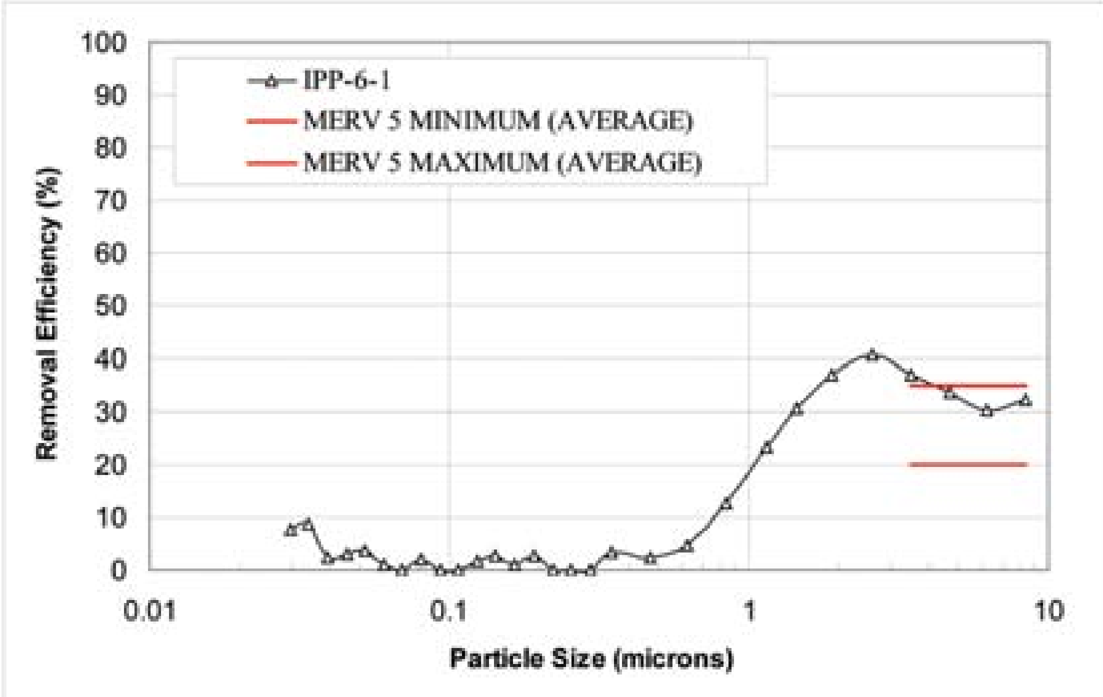


Figure 4-2. Measured Pressure Drops of Unaged MERV 5 Filters

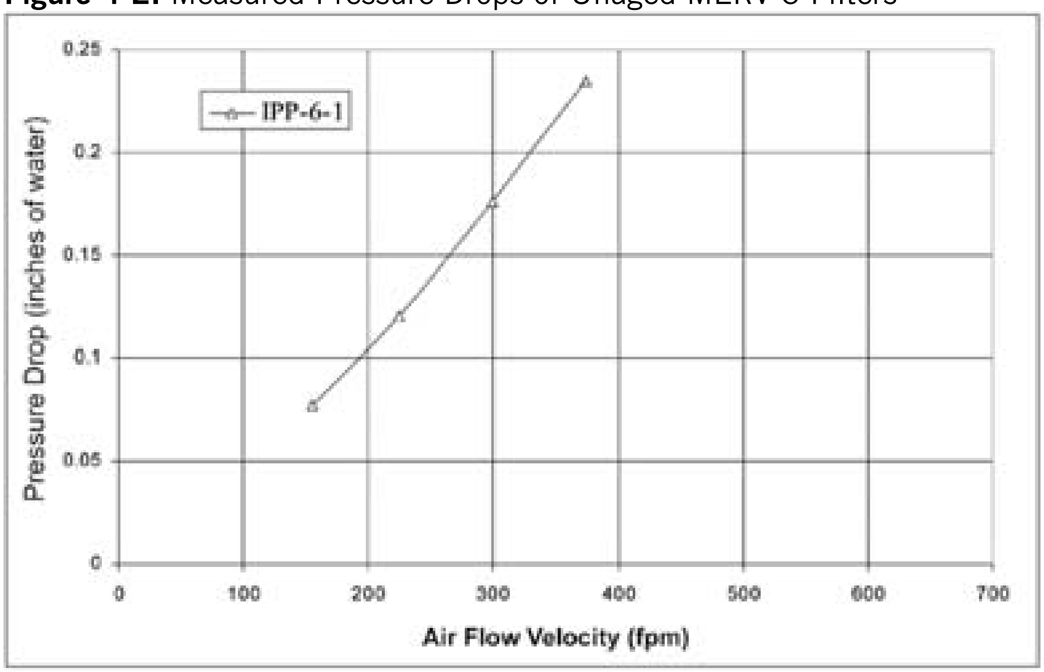


Figure 4-3. Measured Collection Efficiencies of Unaged MERV 6 Filters

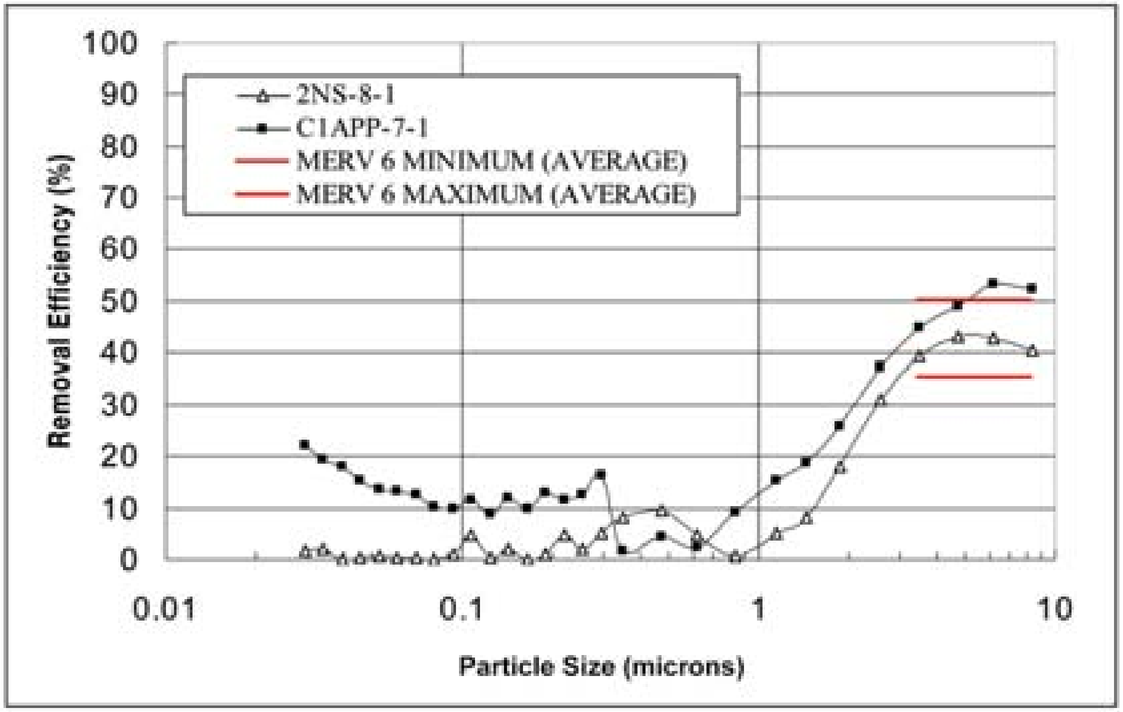


Figure 4-4. Measured Pressure Drops of Unaged MERV 6 Filters

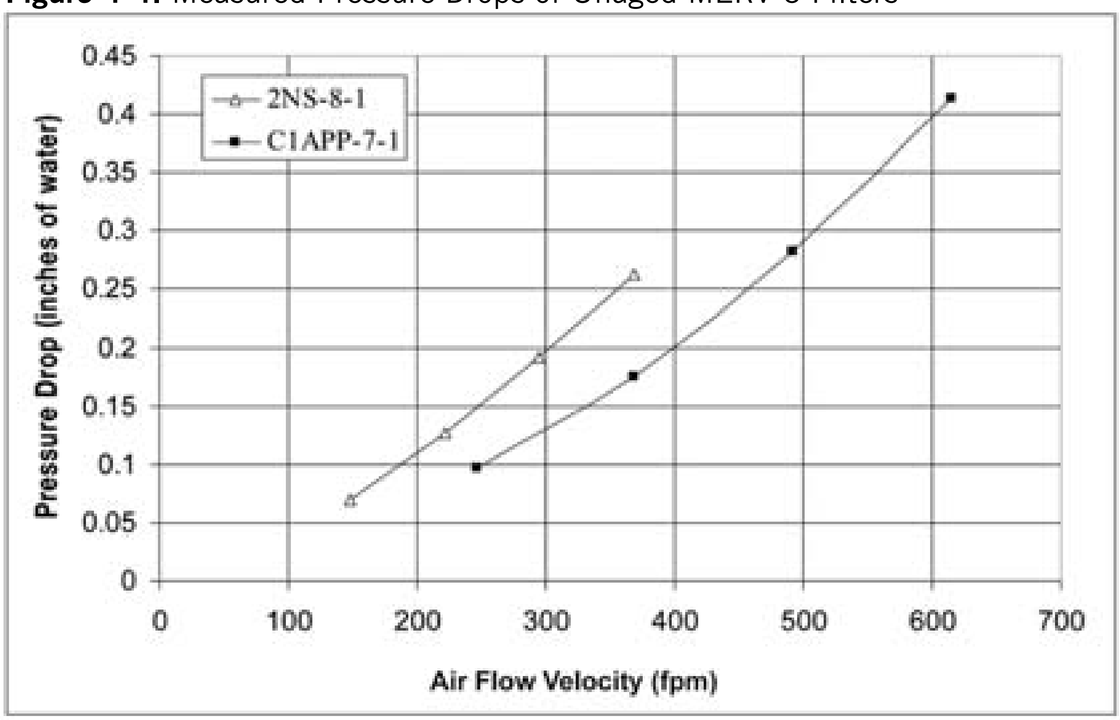


Figure 4-5. Measured Collection Efficiencies of Unaged MERV 7 Filters

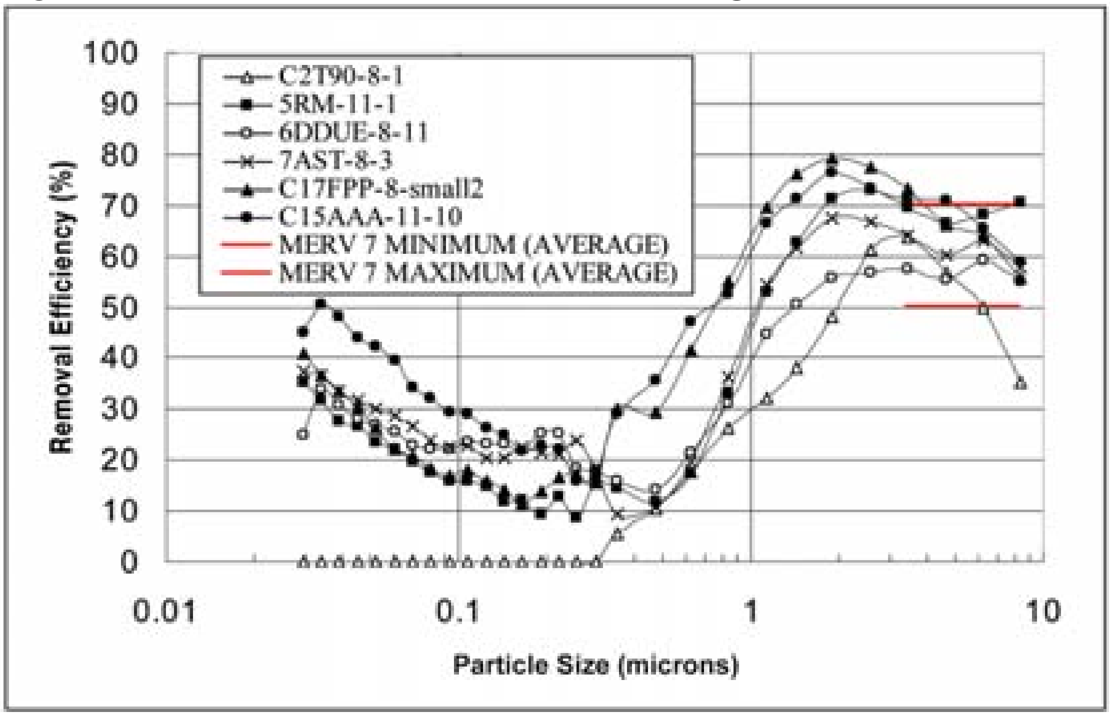


Figure 4-6. Measured Pressure Drops of Unaged MERV 7 Filters

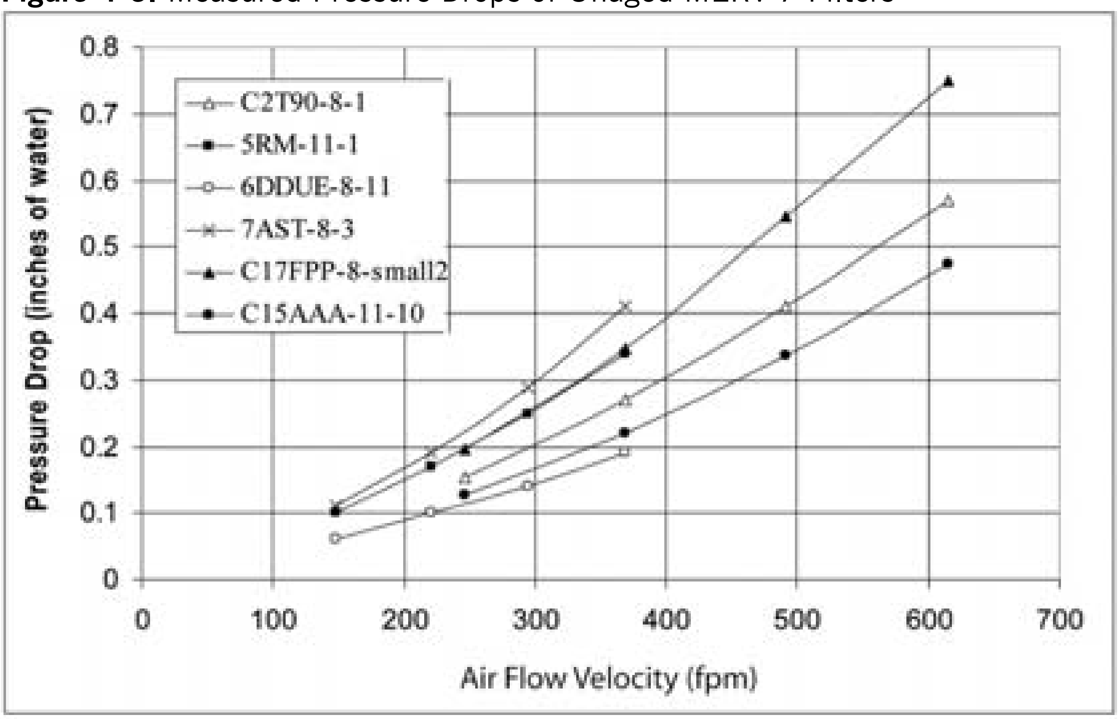


Figure 4-7. Measured Collection Efficiencies of Unaged MERV 8 Filters

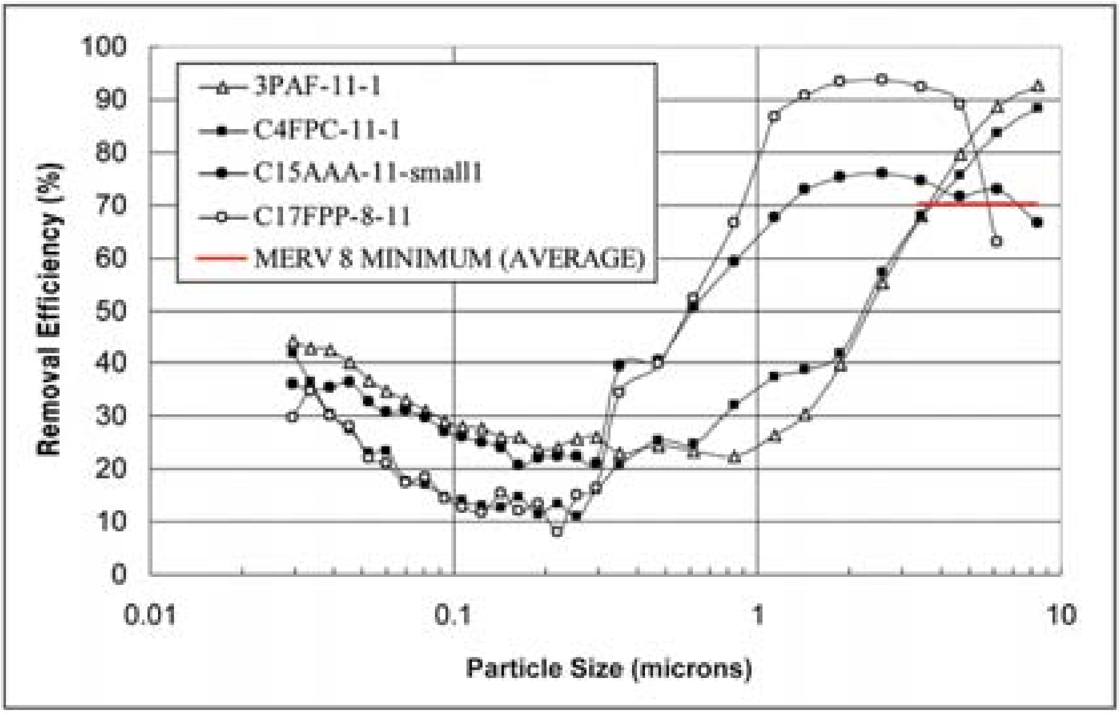


Figure 4-8. Measured Pressure Drops of Unaged MERV 8 Filters

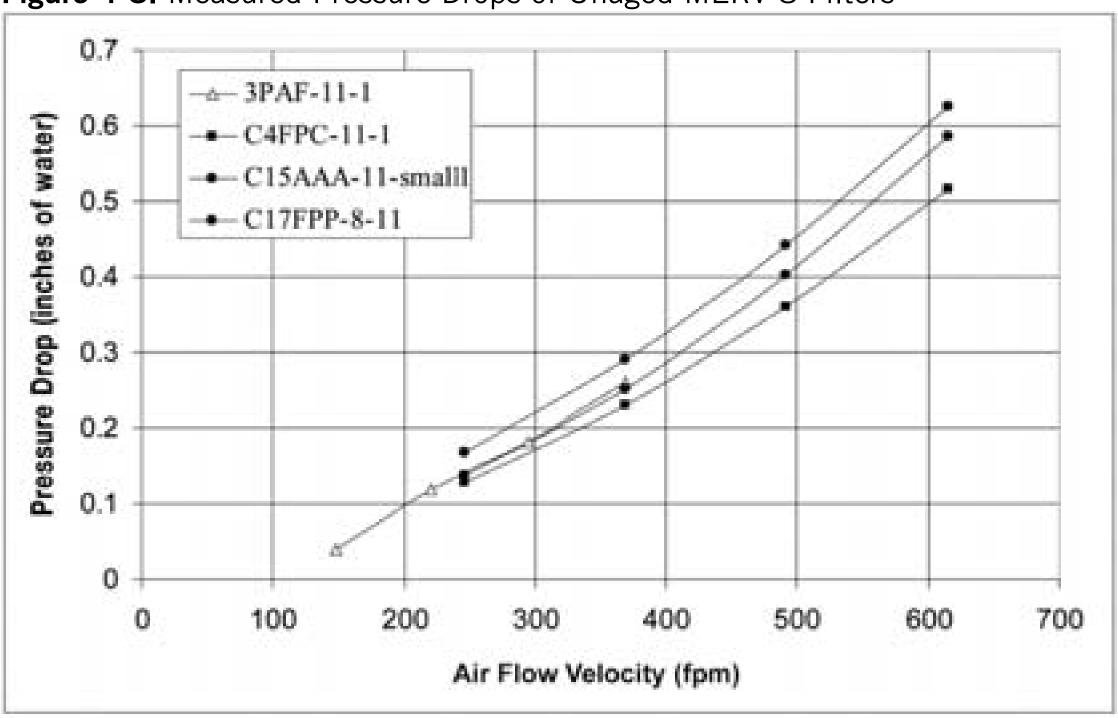


Figure 4-9. Measured Collection Efficiencies of Unaged MERV 10 Filters

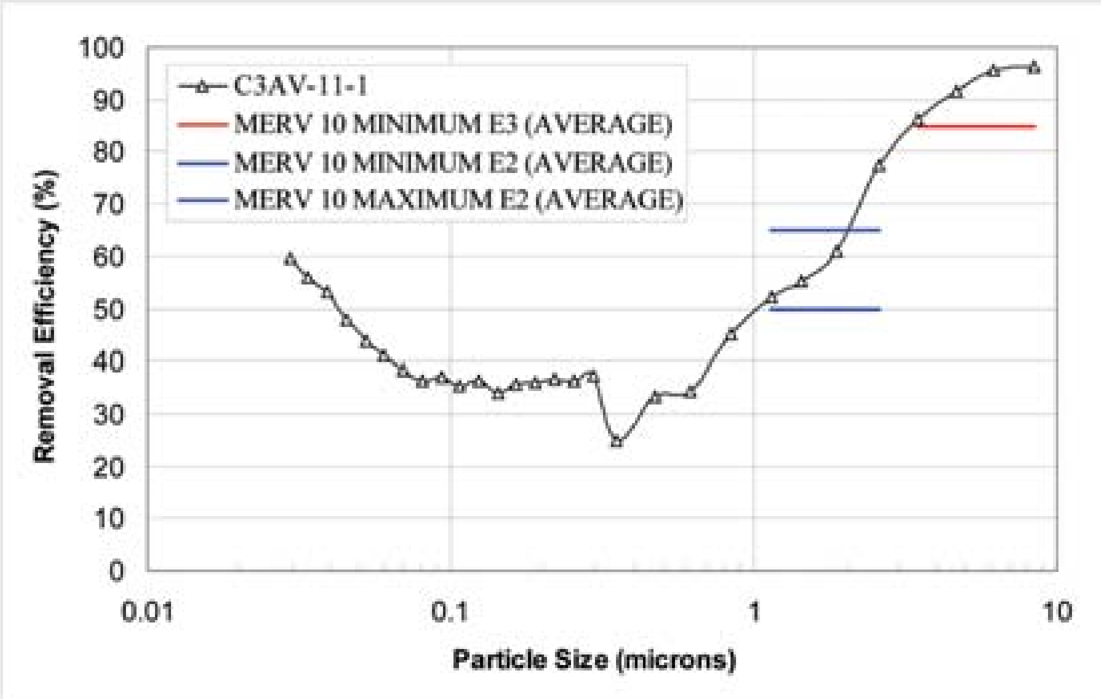


Figure 4-10. Measured Pressure Drops of Unaged MERV 10 Filters

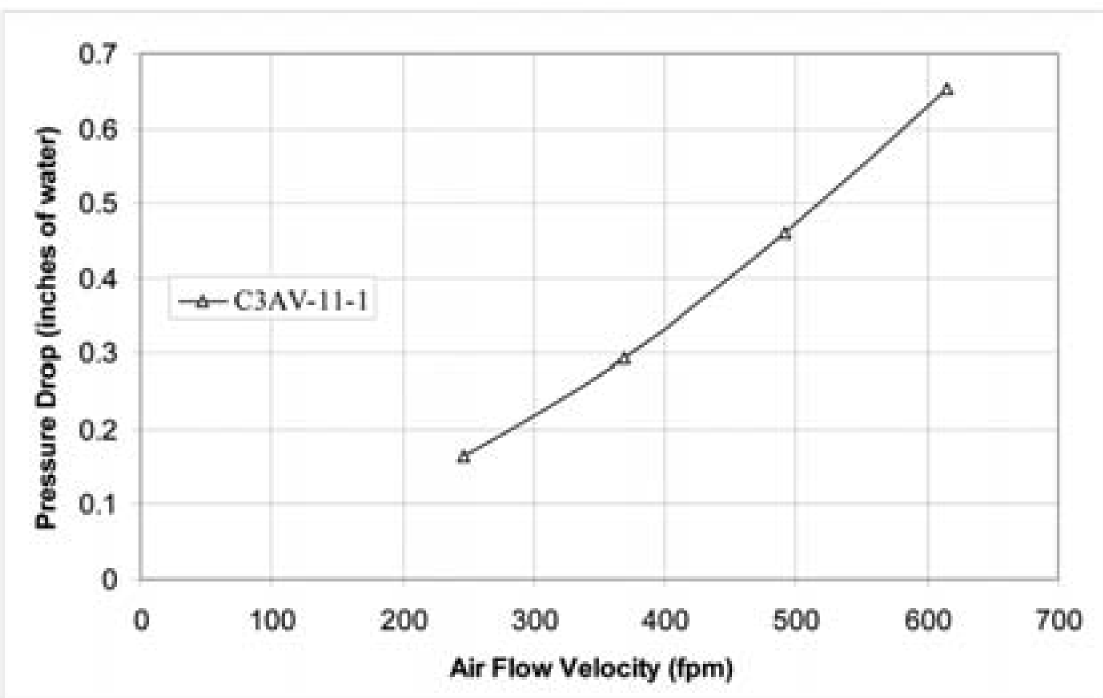


Figure 4-11. Measured Collection Efficiencies of Unaged MERV 12 Filters

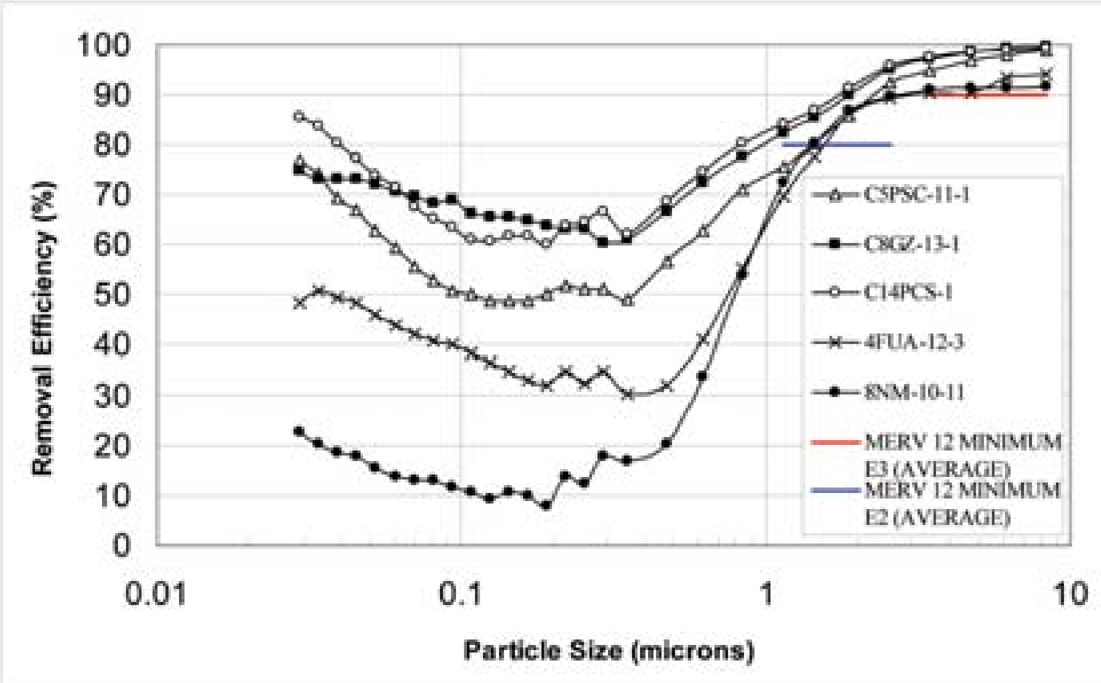


Figure 4-12. Measured Pressure Drops of Unaged MERV 12 Filters

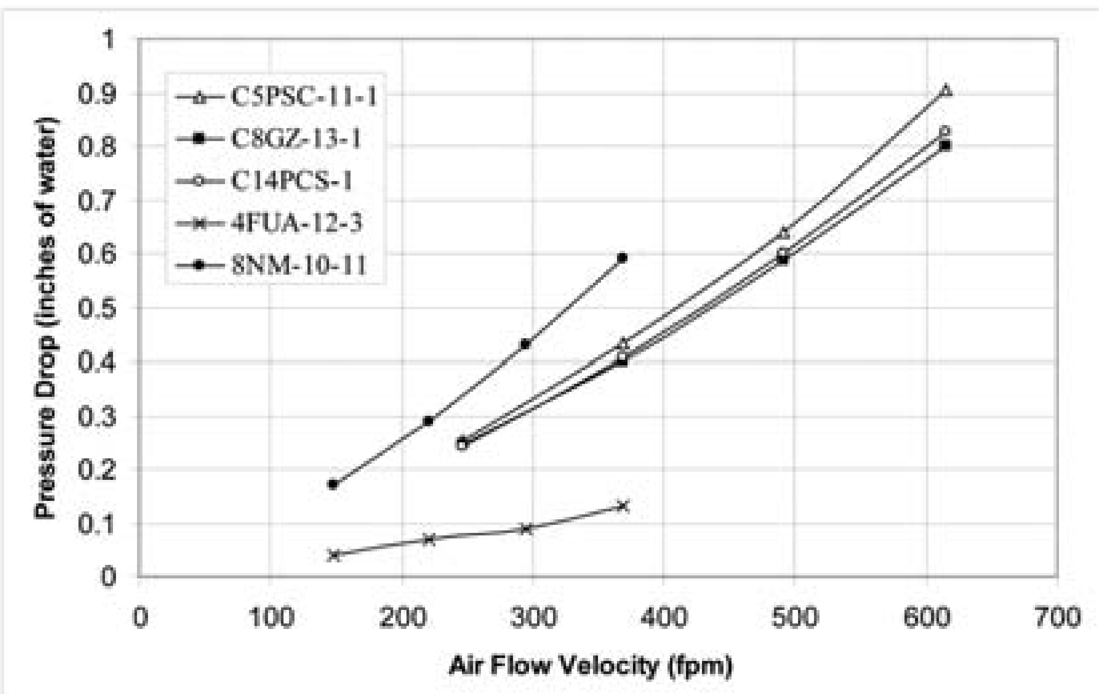


Figure 4-13. Measured Collection Efficiencies of Unaged MERV 14 Filters

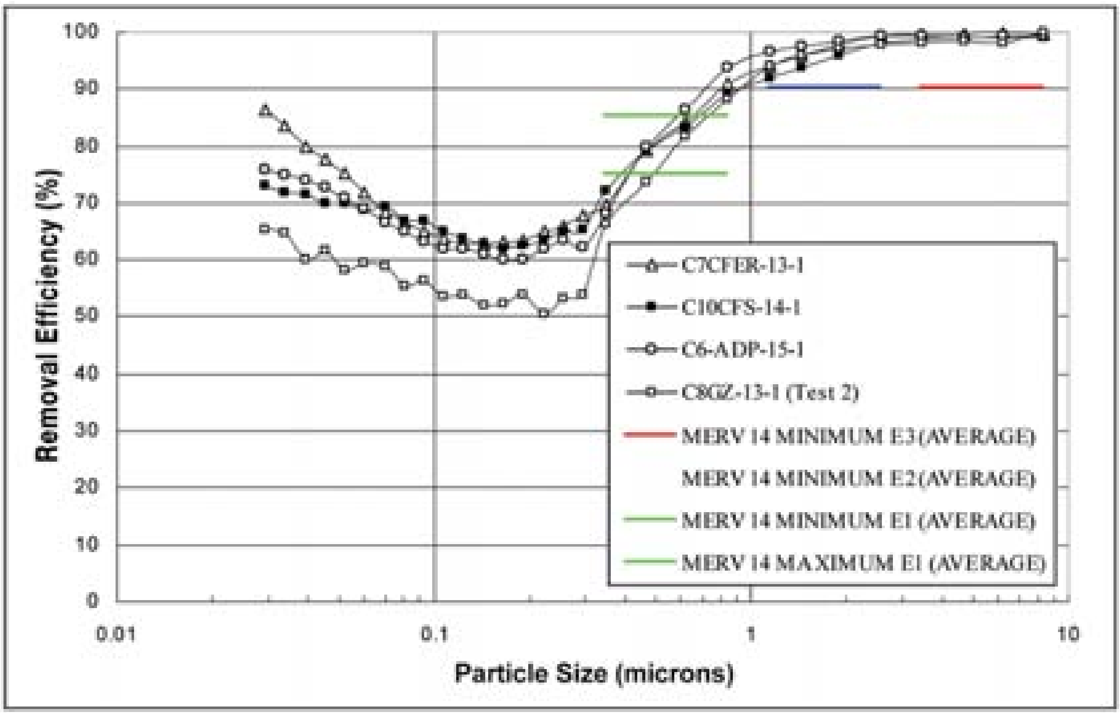


Figure 4-14. Measured Pressure Drops of Unaged MERV 14 Filters (Use of C6-ADP-15-1 data is not recommended as filter was used well beyond its recommended flow rate.)

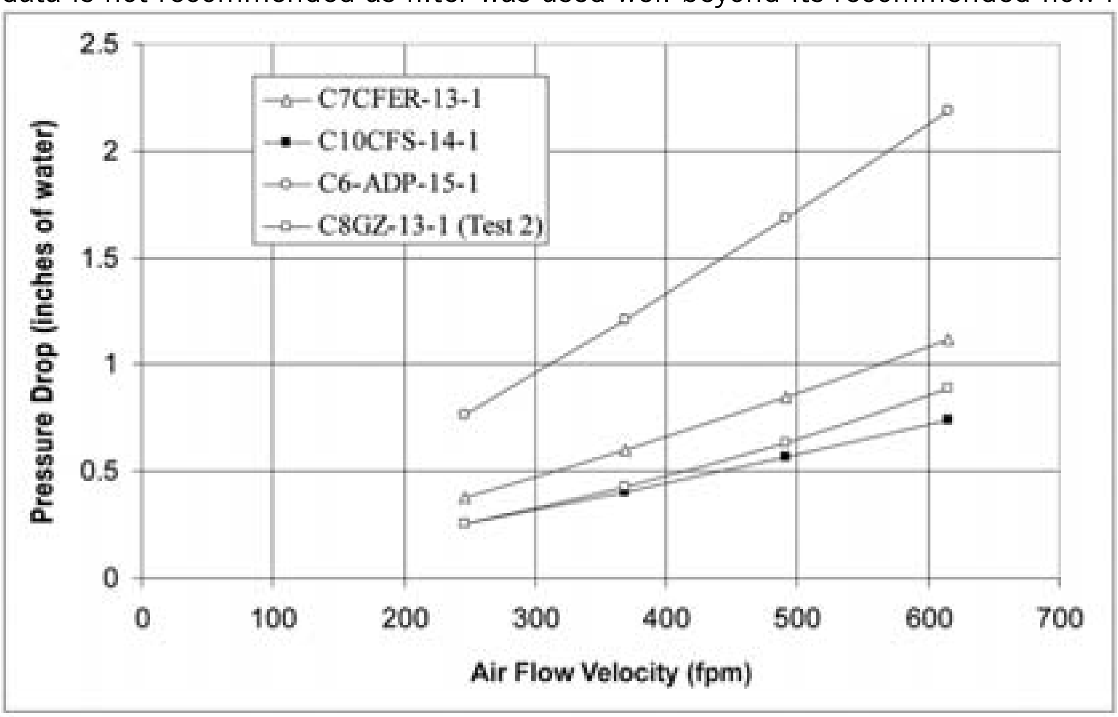


Figure 4-15. Measured Collection Efficiencies of Unaged MERV 16 Filters

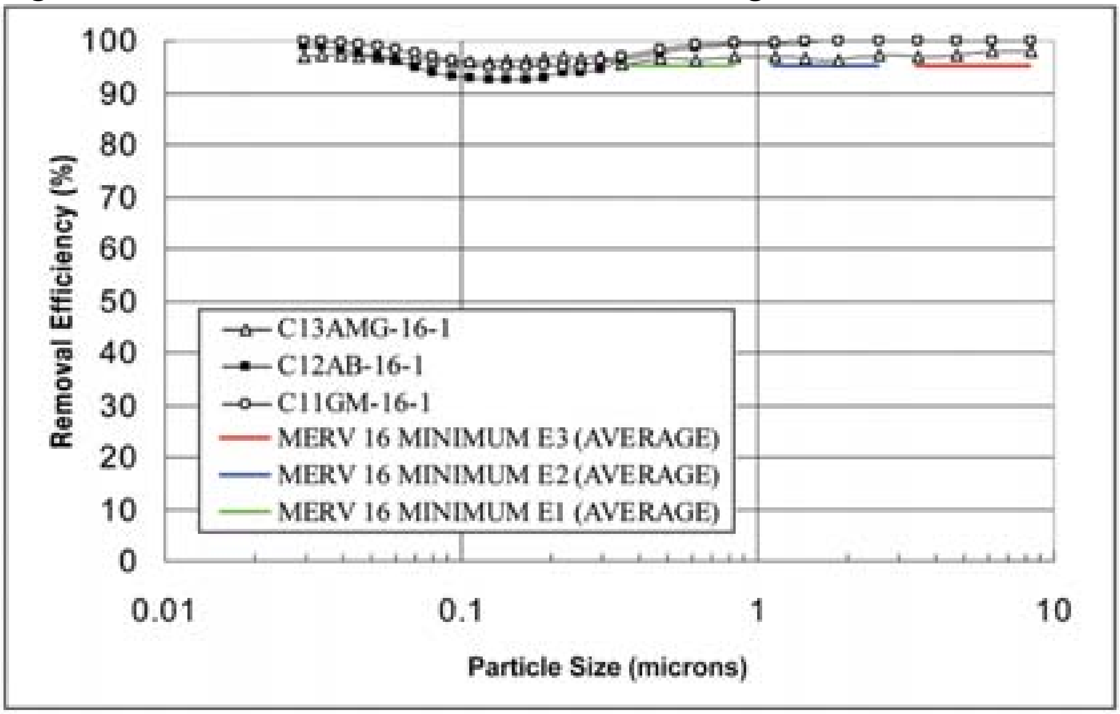


Figure 4-16. Measured Pressure Drops of Unaged MERV 16 Filters

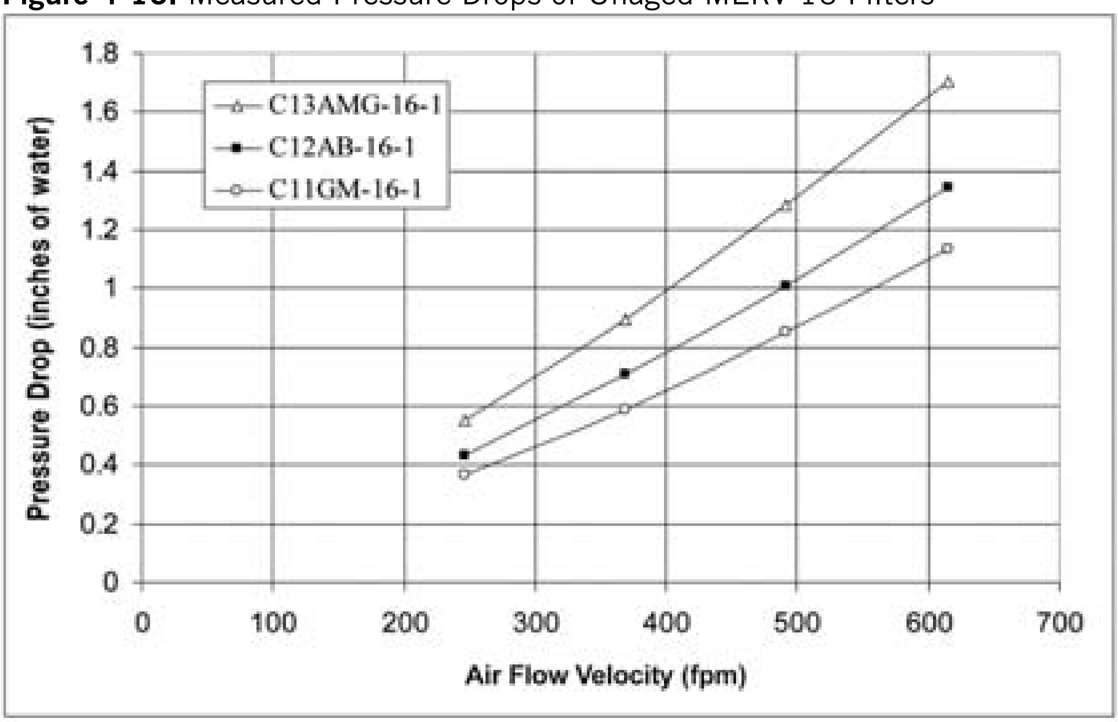


Figure 4-17. Measured Collection Efficiency of Unaged MERV 16+ (HEPA) Filter

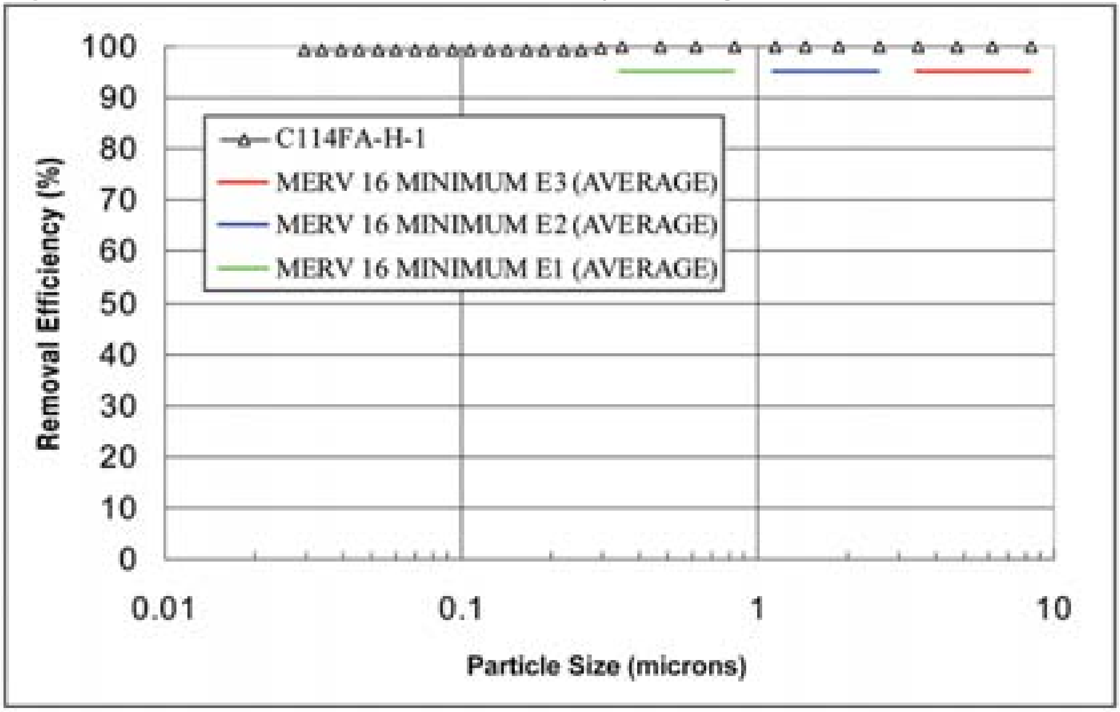
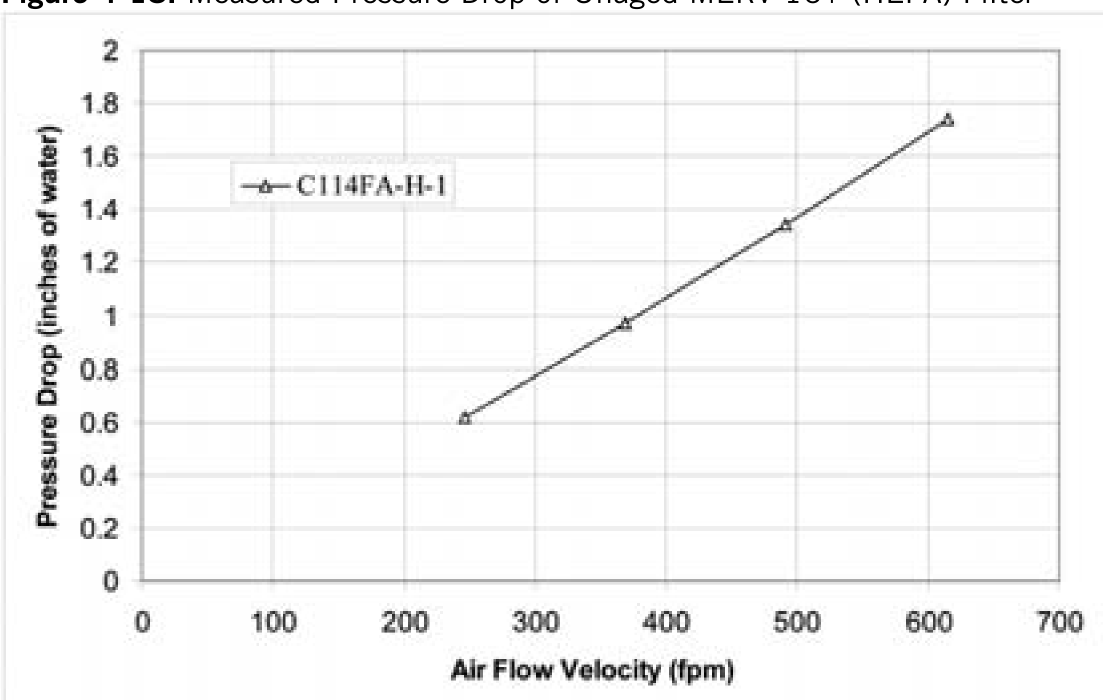


Figure 4-18. Measured Pressure Drop of Unaged MERV 16+ (HEPA) Filter



The most penetrating particle size was consistently in the 0.1 to 0.3 µm range, consistent with typical filtration efficiency curves. The pressure drops of the filters between MERV 5 and 8 did not appear to be substantially different, averaging approximately 0.18 inches of water at 300 fpm for all four MERV ratings. However, the pressure drops of the filters generally increased as the MERV ratings increased past 8, averaging approximately 0.22 inches of water at 300 fpm for MERV 10, approximately 0.34 inches of water at 300 fpm for MERV 12 (with the exception of electrostatic filter 4FUA-12-1), approximately 0.39 inches of water at 300 fpm for MERV 14 (excluding filter C6-ADP-15-1, which was tested well beyond its recommended flow rate), approximately 0.57 inches of water at 300 fpm for MERV 16, and approximately 0.75 inches of water at 300 fpm for the HEPA filter. Therefore, consumers of air filters will need to balance the higher pressure drops and costs of MERV 12 to MERV 16 filters versus the expected increase in performance.

4.1.2 Unaged Electronic Air Cleaners

Table 4-3 summarizes the results from the "off-the-shelf" evaluations of the EACs. As shown in Table 4-3, the measured pressure drops of Units A and P corresponded well with the information provided by the manufacturers, while the pressure drop for Unit H was nearly double the expected value. However, in all three cases, the measured pressure drops were less than 0.12 inches of water at 295 feet per minute, which was approximately one-third less than the pressure drops for MERV 5 to 8 filters. In terms of collection efficiency, the MERV ratings that were determined from the tests ranged from one MERV rating below to three MERV ratings above the manufacturer data. The MERV ratings were also consistent between the two samples of each unit evaluated. As with the filter testing, it should be noted that the testing performed on the current study did not include the dust-loading portion of ANSI/ASHRAE 52.2-1999; therefore, the MERV ratings were determined from the initial collection efficiency portion of the test only. Similarly, while the testing during this study consisted of evaluating pairs of the units, the results may not be representative of typical performance.

Table 4-3. Results from the Inert Aerosol Evaluations of "Off-the-Shelf" Electronic Air Cleaners (Two units of Each Type were Tested)

Identifier for Charts and Tables	Dimensions (inches)	Capacity (CFM)	MERV Rating (literature)	MERV Rating (testing)[a]	MERV Efficiencies (%) E1 – 0.3 – 1.0 µm E2 – 1.0 – 3.0 µm E3 – 3.0 – 10 µm	Literature Pressure Drop (in. w.g.)	Measured Pressure Drop (in. w.g.)	Notes
A	16 x 25	Up to 2,000	> 94% at 0.35 µm (MERV 15)	15, 14	E1= 90.8, 84.2 E2= 94.4, 93.1 E3= 96.6, 97.9	0.17 at 500 fpm	0.11 and 0.12 at 295 fpm	MERV 15 requires E1 > 85%
H	20 x 20	Up to 1,400	Up to MERV 12 at 492 fpm	15, 15	E1=91.5, 92.7 E2= 97.2, 96.9 E3= 98.8, 98.1	0.06 at 295 fpm	0.11 and 0.11 at 295 fpm	MERV 16 requires E1 > 95%
P	20 x 20	Up to 1,400	none	14, 14	E1= 82.5, 84.0 E2= 95.3, 95.1 E3= 96.9, 97.1	0.11 at 500 fpm	0.08 and 0.06 at 295 fpm	MERV 15 requires E1 > 85%

[a] Two units tested.

Figures 4-19 and 4-20 graphically illustrate the collection efficiencies and pressure drops that were measured for the "off-the-shelf" EACs. As shown in Figure 4-19, the collection efficiency curves obtained for the EACs were quite similar in shape. In addition, collection efficiencies measured with the OPC (0.3 to 10 µm) generally corresponded very well with the collection efficiencies measured with the SMPS (0.03 to 0.3 µm). As shown in Figure 4-20, the pressure drops of the EACs were generally similar or up to 33% less than filters with MERV ratings between 5 and 8. Given that the EACs possessed MERV ratings of 14 and 15, at least initially, they appeared to offer considerably higher collection efficiency than air filters for a given pressure drop.

Figure 4-19. Measured Collection Efficiency of Unaged Electronic Air Cleaners

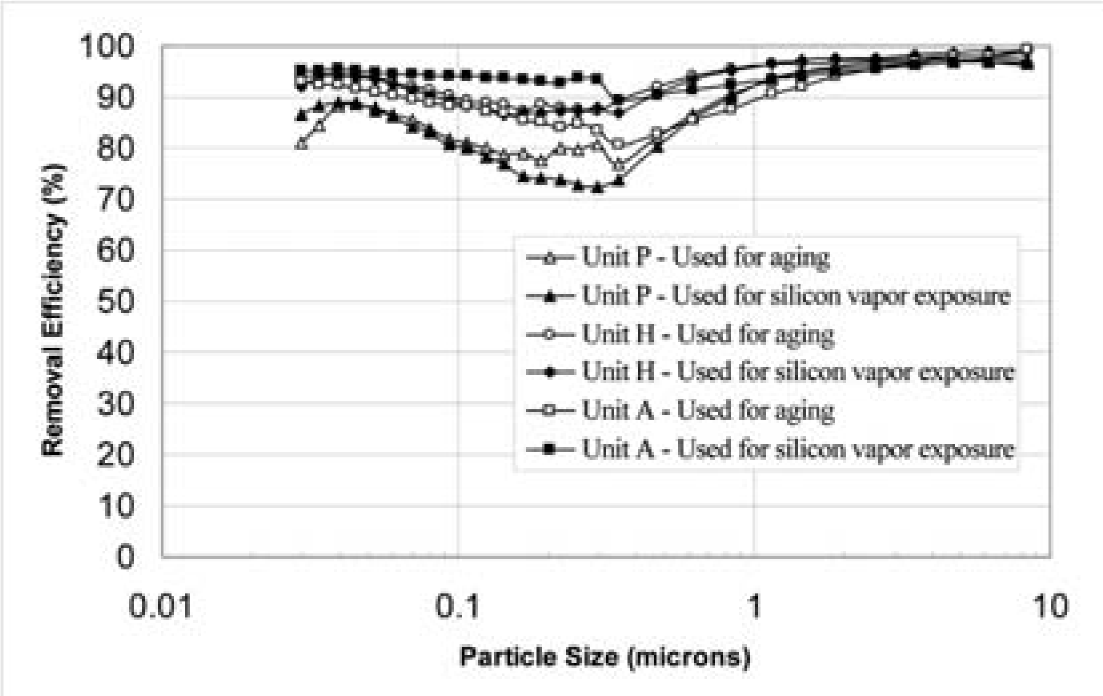
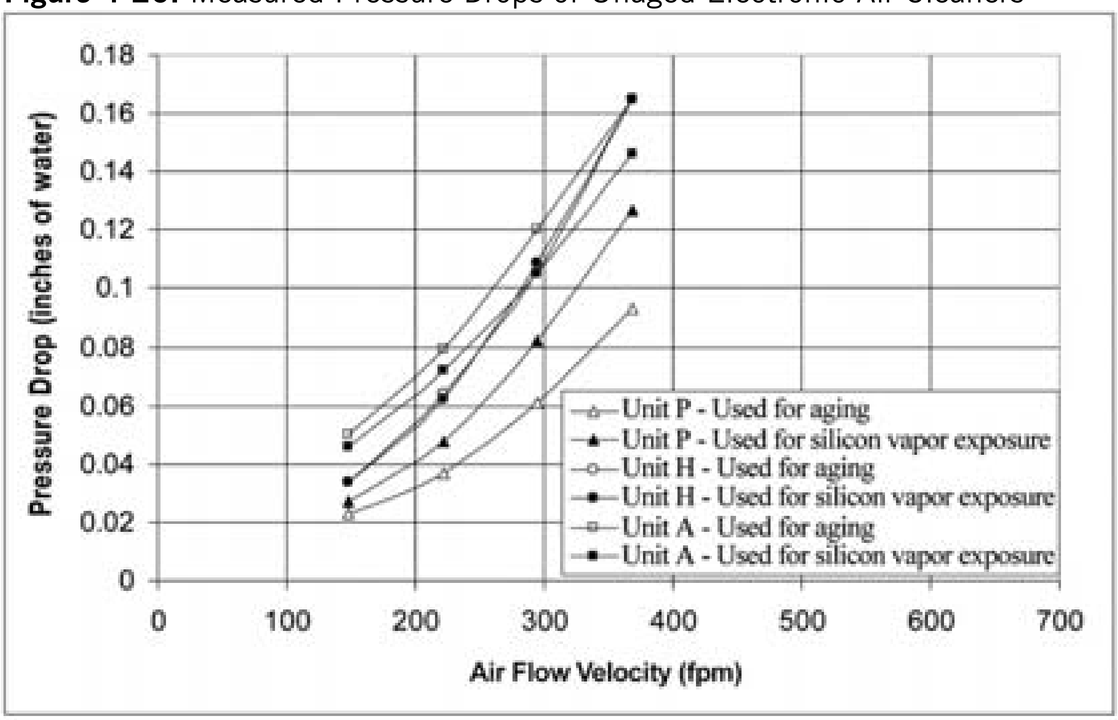


Figure 4-20. Measured Pressure Drops of Unaged Electronic Air Cleaners



4.2 Bioaerosol Penetration

A select group of filters (seven) and EACs (three) were evaluated against a bioaerosol challenge. The purpose of the bioaerosol tests was to compare the penetration of a bioaerosol to the penetration of a similarly-sized inert aerosol to determine whether there were any significant differences between the penetration of bioaerosol and inert particles.

All of the bioaerosol tests were performed at the same airflow rate as the inert aerosol tests, which was the maximum flow rate the units would likely encounter in actual use. The pressure drops of the devices were also evaluated at the test flow rate. For filter 2NS-8-1, the same filter was used for both the inert and bioaerosol tests. However, for the remaining air cleaners, use of the same device was not feasible. Therefore, a unit of the same make, model, and size was used for both the bioaerosol and inert aerosol. (For one filter, C11GM-16-BIO, a 12" x 24" x 12" filter was evaluated versus the bioaerosol, while a 24" x 24" x 12" filter was used in the inert particle evaluations. However, the same filtration velocity of 492 fpm was used.) No aging or conditioning of the filters or the EACs was performed prior to the bioaerosol evaluations so that direct comparisons to the inert aerosol evaluations of "off-the-shelf" units (Section 4.1) could be made. A complete listing of the results from these evaluations for each air cleaner is provided in Appendix F. A summary of the results is provided below.

Table 4-4 summarizes the results from the bioaerosol tests. For the convenience of the reader, both the filter evaluations and EAC evaluations are included in Table 4-4. As shown in Table 4-4, the bioaerosol was consistently aerosolized chiefly as single spores, with mass median aerodynamic diameters just under 1 µm. (The standard deviations measured for the bioaerosol indicated that the majority of the bioaerosol particles possessed aerodynamic diameters within a factor of two of the mass median aerodynamic diameter.) Figures 4-21 through 4-30 provide a graphical comparison between the inert aerosol and bioaerosol test results. In each figure, the bioaerosol collection efficiency is plotted along with the standard deviation of the bioaerosol particle diameter and the standard deviation of the measured collection efficiency as calculated using equation 9 from Section 3.2.

Similar to previously reported results (RTI, 2004), in nine of the ten tests, the measured bioaerosol collection efficiencies generally exceeded the average collection efficiency for inert particles with physical particle diameters between 0.3 and 1 µm (E1) but were generally less than or equivalent to the inert aerosol collection efficiency results for 1 to 3 µm particles (E2). These results are consistent with the measured mass median aerodynamic diameters of the bioaerosol. The only exception was filter 6DDUE-8, for which a low (6%) bioaerosol collection efficiency was measured. However, as shown in Figure 4-24, when the standard deviation of the bioaerosol results for filter 6DDUE-8 is taken into consideration, the test results are likely in reasonable agreement. Overall the results indicate that bioaerosol particles are collected similarly to comparably sized inert particles.

Table 4-4. Summary of the Results from the Bioaerosol Evaluations

Air Cleaner	Description	Air Velocity Coefficient of Variance	Aerosol Concentration Coefficient of Variance		Mass Median Aerodynamic Particle Size in µm (geometric standard deviation)	Correlation Coefficient or Collection Efficiency and Combined Standard Deviation of Penetration	MERV Efficiencies (%) From inert evaluations E1– 0.3 – 1.0 µm E2 – 1.0 – 3.0 µm E3 – 3.0 – 10 µm
			Upstream	Downstream			
None (820 cfm)	NA	19.4%	10%	7%	0.71 (2.2)	0.995	NA
2NS-8-1	Pleated polyester and cotton blend – residential	18.1%	14%	16%	0.86 (2.1)	14 ± 18%	E1= 5.9 E2= 15.7 E3= 41.3
4FUA-12-1	Pleated polypropylene and polyolefin electrostatic – residential	20.8%	10%[a]	27%[a]	0.92 (2.0)	50 ± 14%[a]	E1= 39.7 E2= 80.8 E3= 92.1
8NM-10-1	Pleated electrostatic – residential	25.4%	9%	6%	0.95 (2.1)	40 ± 6%	E1= 31.2 E2= 82.4 E3= 91.4
6DDUE-8-12	Pleated electet – residential	21.0%	13%	16%	0.72 (2.2)	6 ± 19%	E1= 20.6 E2= 51.9 E3= 56.8
EAC Model A	EAC	17.8%	28%	115%[b]	0.70 (2.2)	93 ± 8%	E1[e]= 90.8, 84.2 E2[e]= 94.4, 93.1 E3[e]= 96.6, 97.9
EAC Model H	EAC	21.2%	21%	57%[b]	0.81 (2.1)	89 ± 7%	E1[e]= 91.5, 92.7 E2[e]= 97.2, 96.9 E3[e]= 98.8, 98.1
EAC Model P	EAC	18.6%	18%	68%[b]	0.71 (2.1)	95 ± 4%	E1[e]= 82.5, 84.0 E2[e]= 95.3, 95.1 E3[e]= 96.9, 97.1
None (984 cfm)	NA	19.5%	15%	9%	0.82 (2.1)	1.034	NA
C15AAA-11-BIO[c]	Pleated electrostatic prefilter – commercial	16.7%	11%	4%	0.99 (2.1)	62 ± 4%[c]	E1= 47.5[c], 41.1[d] E2= 72.9[c], 71.9[d] E3= 71.4[c], 66.6[d]
C17FPP-8-BIO[c]	Pleated electrostatic prefilter – commercial	23.5%	15%	9%	0.86 (2.0)	41 ± 11%[c]	E1= 39.1[c], 48.3[d] E2= 75.5[c], 91.1[d] E3= 64.7[c], 81.3[d]
C11GM-16-BIO[c]	5% DOP Pleated microfiberglass – commercial	19.5%	13%	52%[b]	0.64 (2.2)	99.8 ± 0.1%[c]	E1= 98.6[d] E2= 99.9[d] E3= 100[d]

[a] One sample point was excluded because it differed by at least an order of magnitude (statistical outlier).
[b] Downstream results demonstrated a high CV because the concentrations were very low, and for some samples approaching the detection limit of the analytical method.
[c] Test filter had a 12" x 24" cross section and a flow rate of 984 cfm was used (492 fpm).
[d] Test filter had a 24" x 24" cross section and a flow rate of 1968 cfm was used (492 fpm).
[e] Two EACs of each type were evaluated using inert particles.

Figure 4-21. Comparison Between Bioaerosol Collection Efficiency and Inert Collection Efficiency Measurements for Filter 2NS-8-1

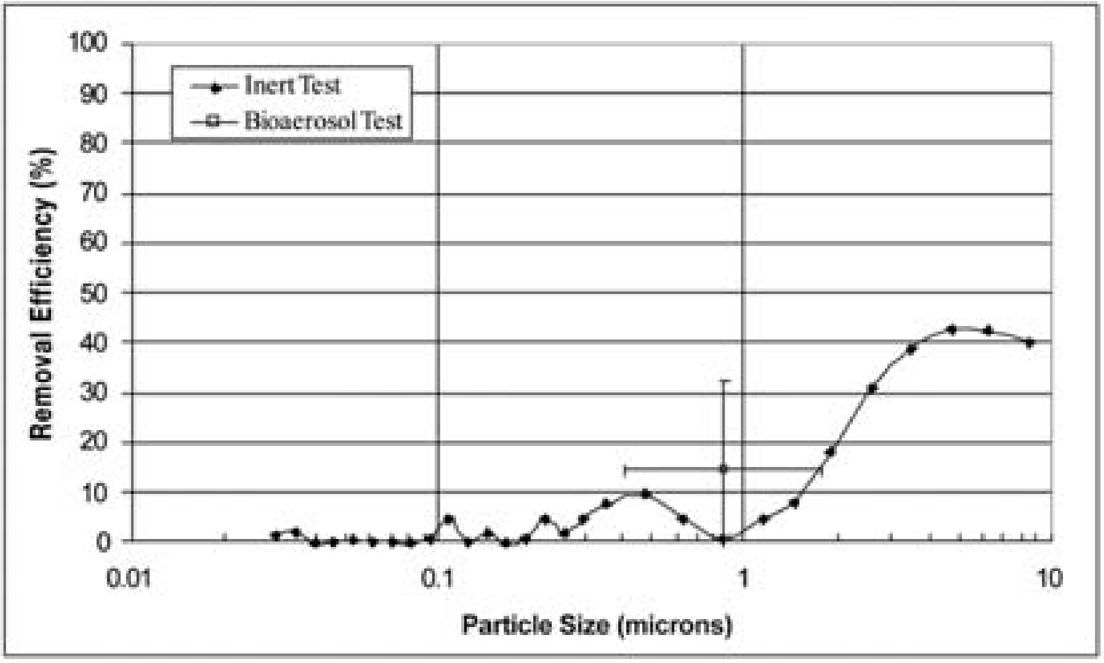


Figure 4-22. Comparison Between Bioaerosol Collection Efficiency and Inert Collection Efficiency Measurements for Filter 4FUA-12-1

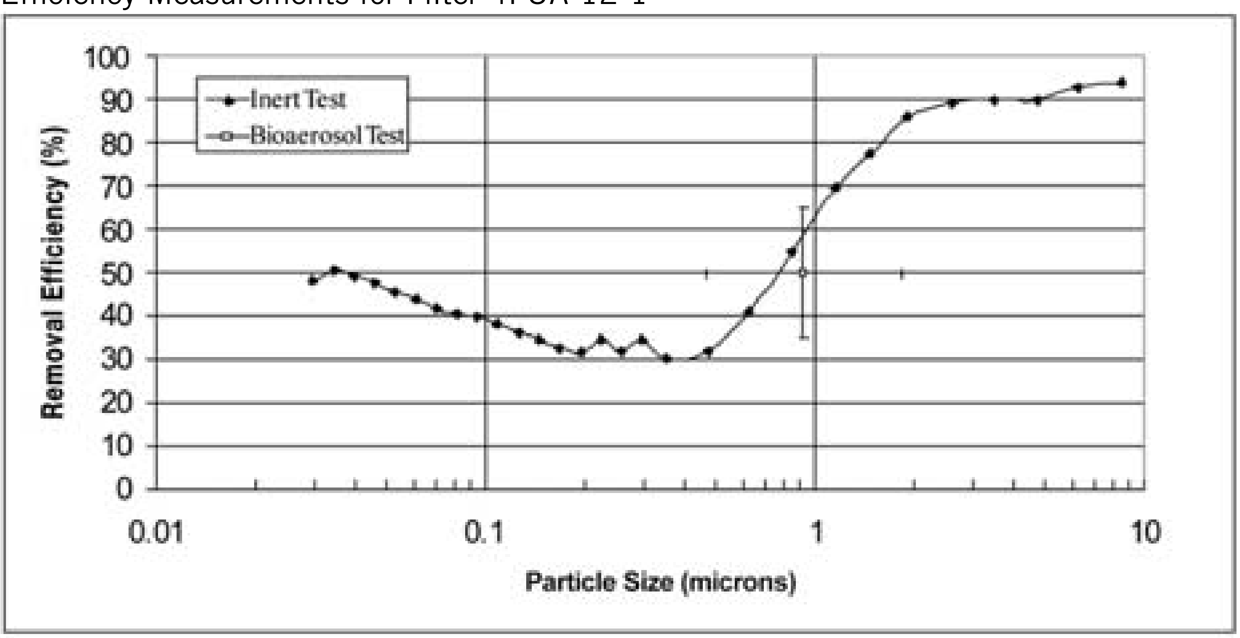


Figure 4-23. Comparison Between Bioaerosol Collection Efficiency and Inert Collection Efficiency Measurements for Filter 8NM-10-1

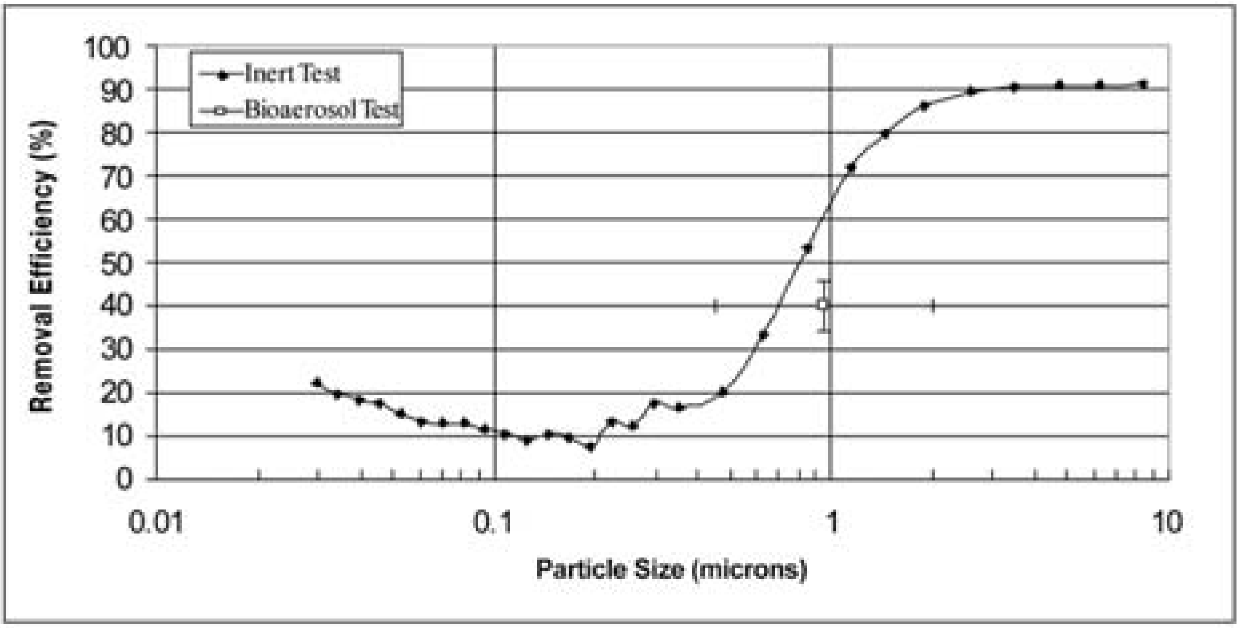


Figure 4-24. Comparison Between Bioaerosol Collection Efficiency and Inert Collection Efficiency Measurements for Filter 6DDUE-8-12

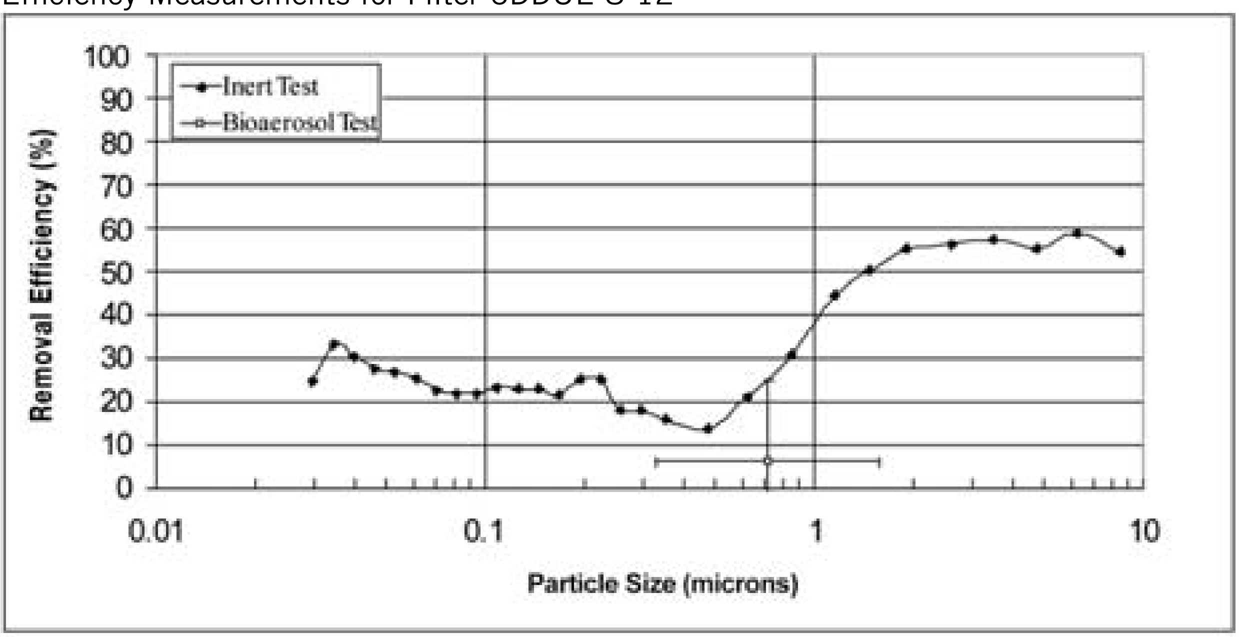


Figure 4-25. Comparison Between Bioaerosol Collection Efficiency and Inert Collection Efficiency Measurements for Electronic Air Cleaner A

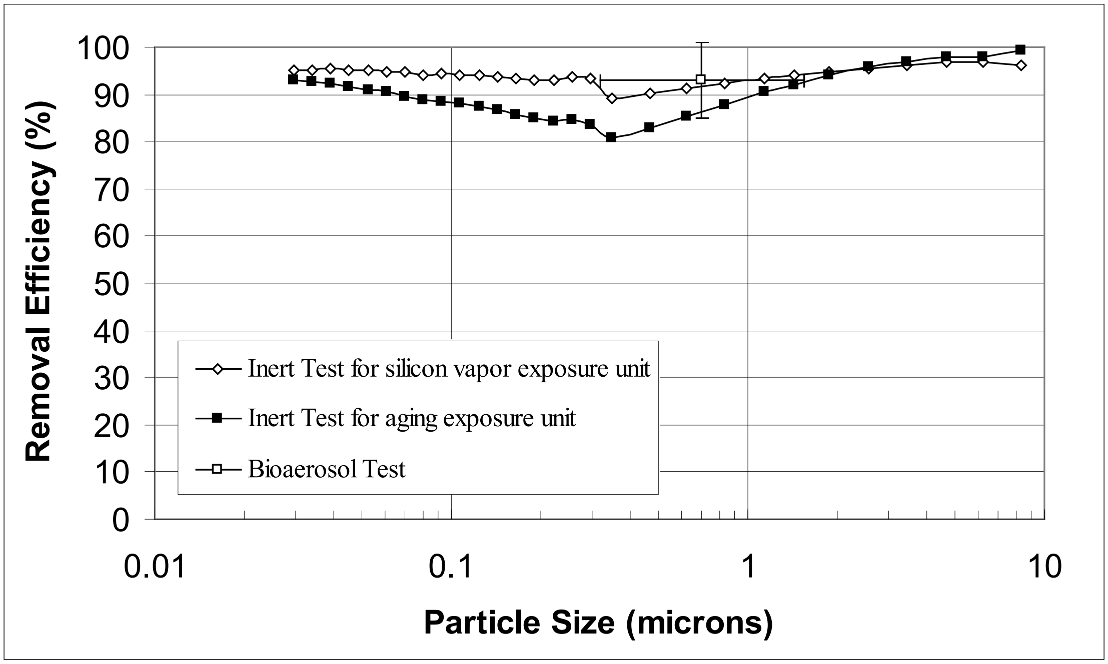


Figure 4-26. Comparison Between Bioaerosol Collection Efficiency and Inert Collection Efficiency Measurements for Electronic Air Cleaner H

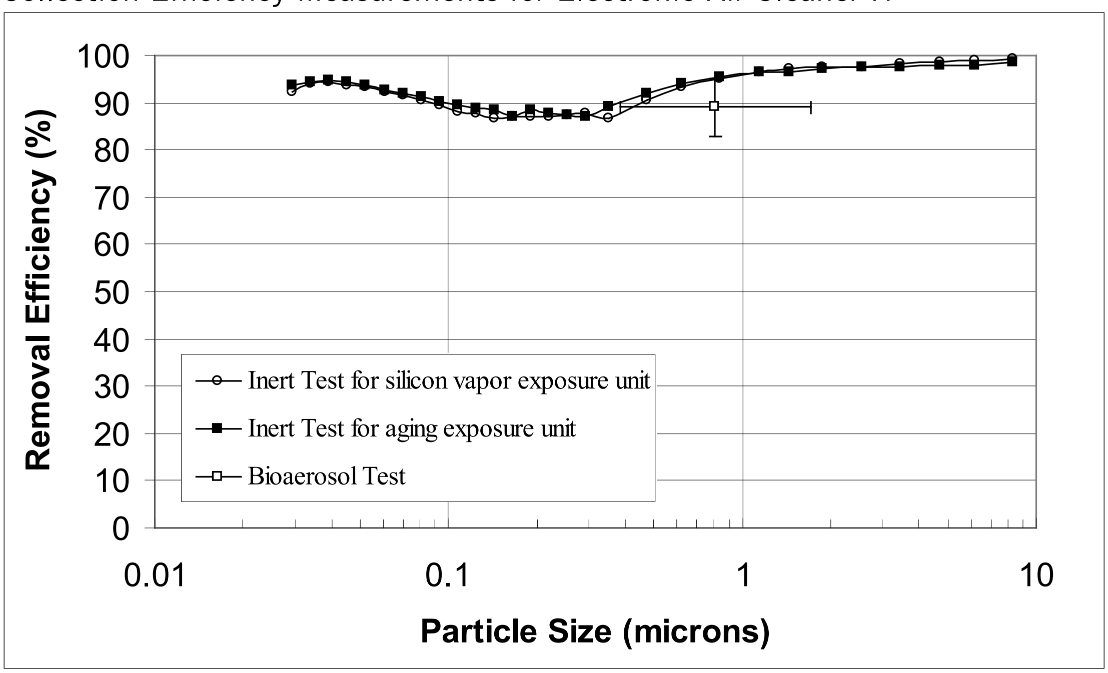


Figure 4-27. Comparison Between Bioaerosol Collection Efficiency and Inert Collection Efficiency Measurements for Electronic Air Cleaner P

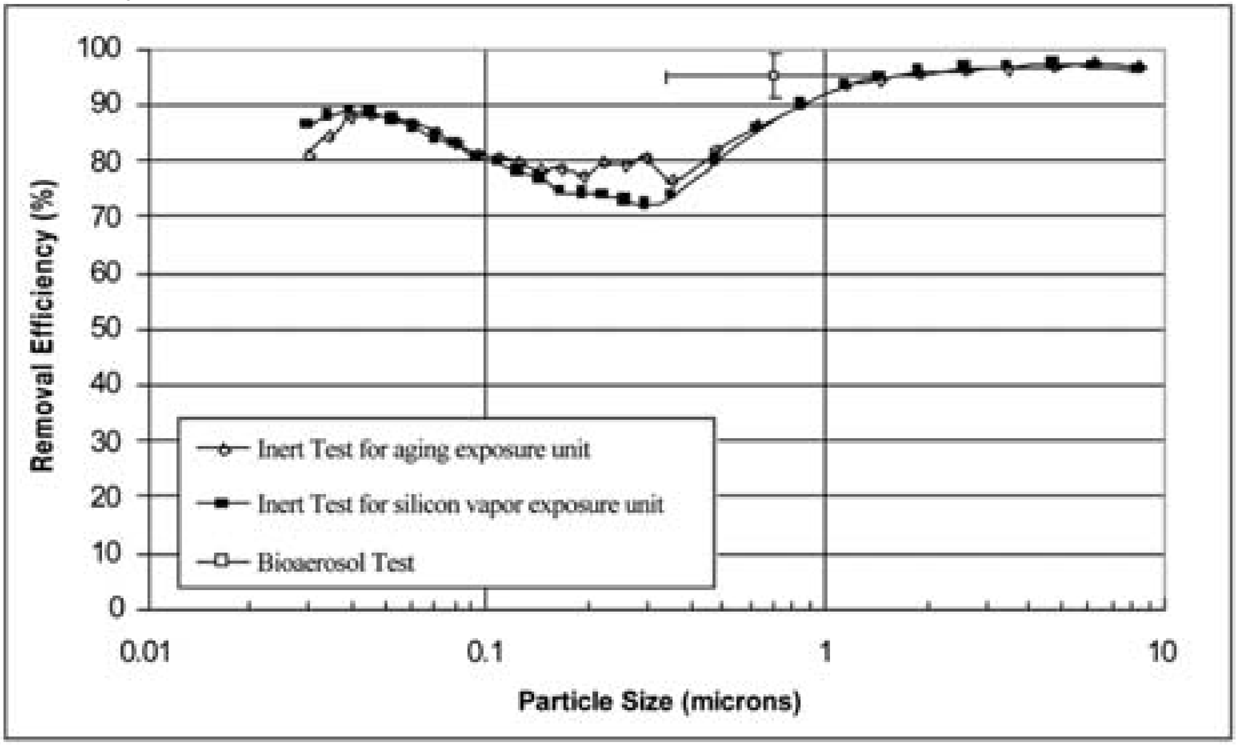


Figure 4-28. Comparison Between Bioaerosol Collection Efficiency and Inert Collection Efficiency Measurements for Filter C15AAA-11-BIO

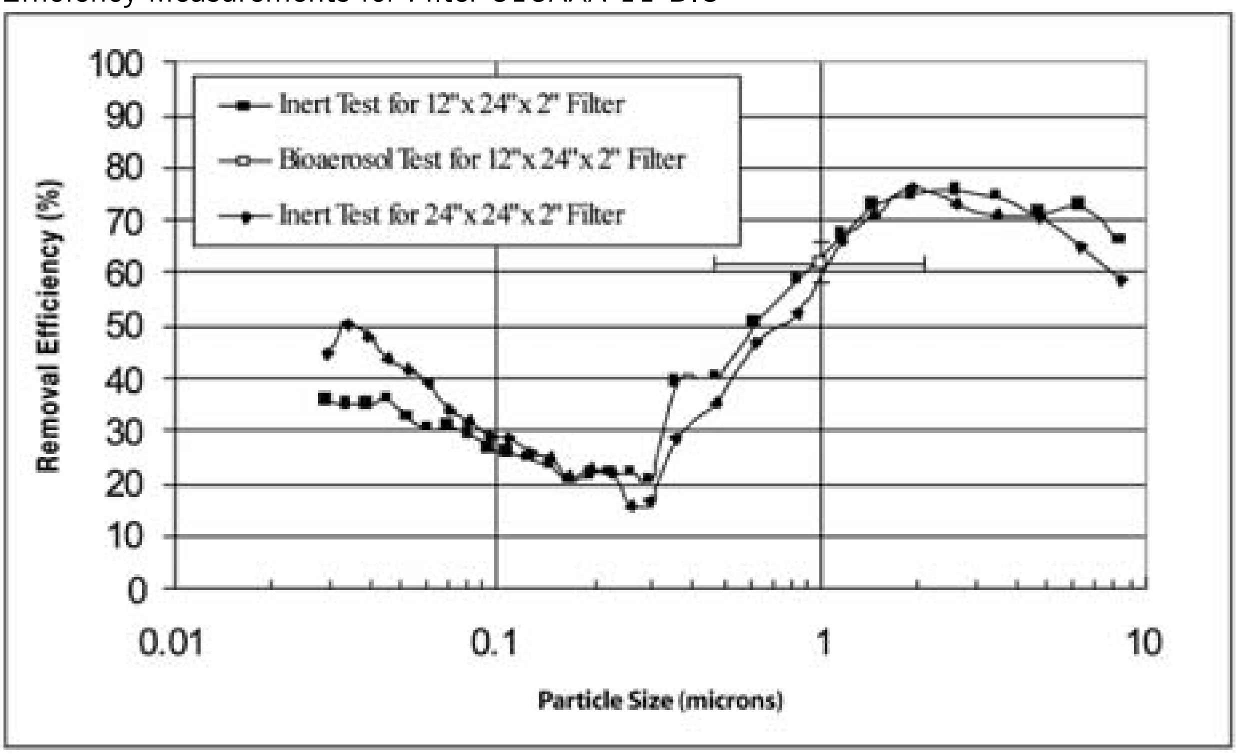


Figure 4-29. Comparison Between Bioaerosol Collection Efficiency and Inert Collection Efficiency Measurements for Filter C17FPP-8-BIO

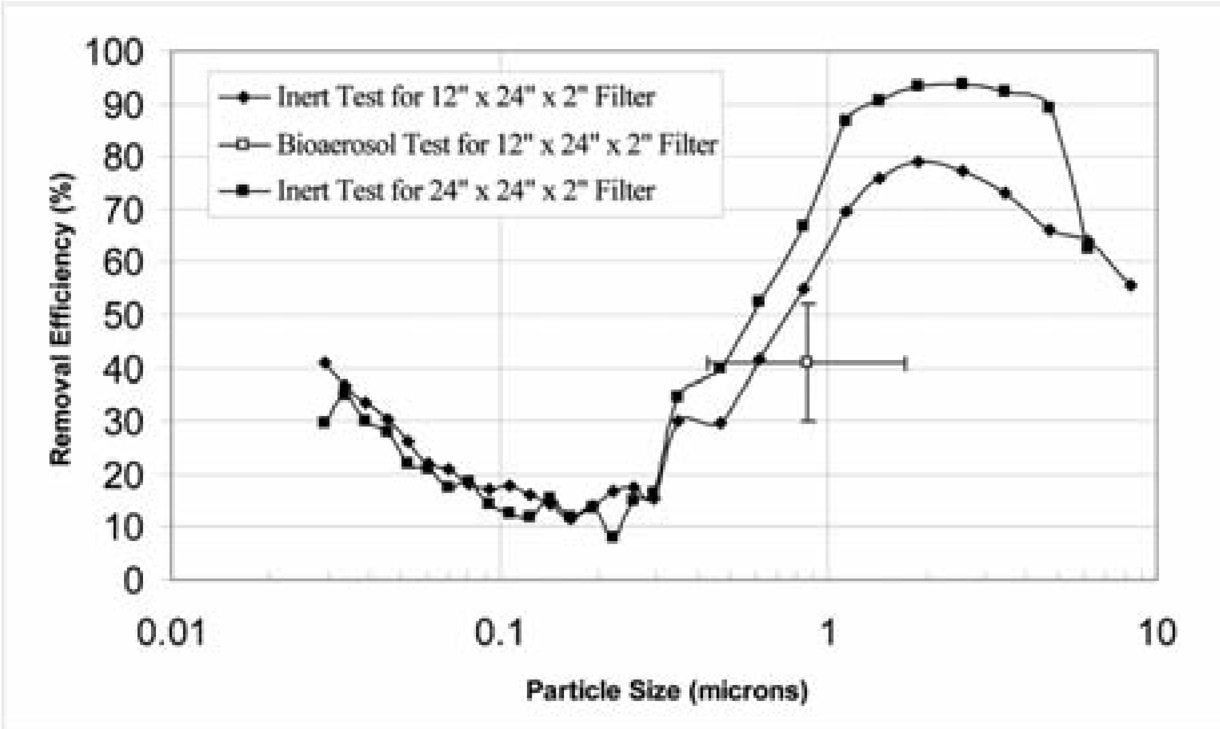
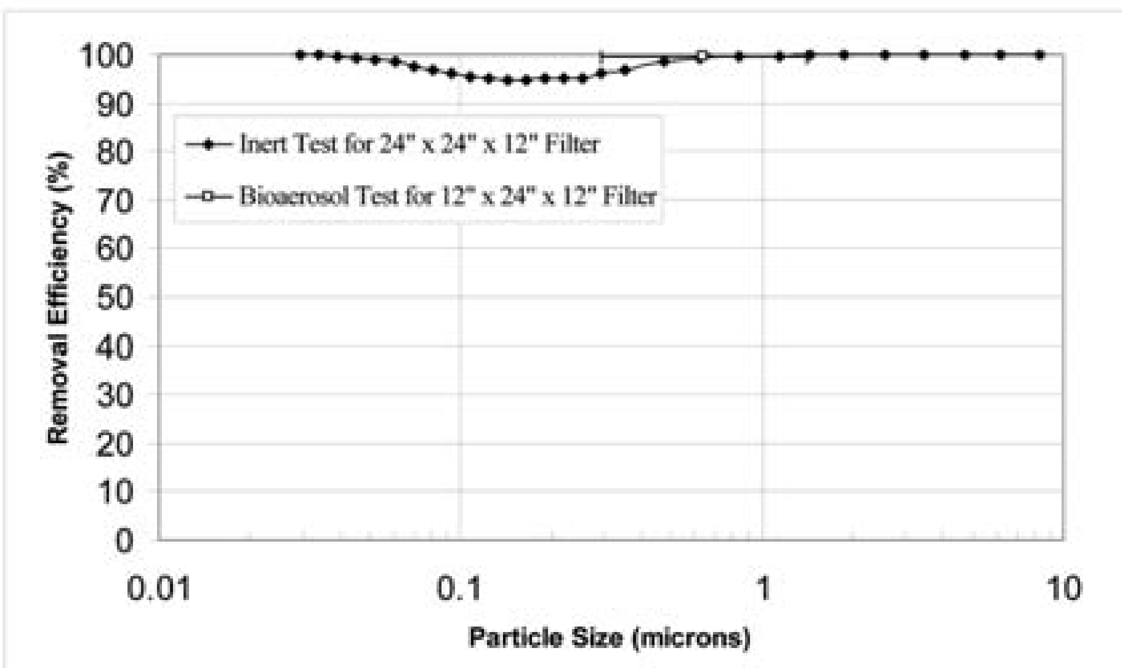


Figure 4-30. Comparison Between Bioaerosol Collection Efficiency and Inert Collection Efficiency Measurements for Filter C11GM-16-BIO



4.3 Results from the Aging Evaluations

For a select group of both filters (seven) and EACs (three), aging was performed in conjunction with inert aerosol testing to examine the effect of dust loading in actual use environments on the collection efficiencies and pressure drops of the units. All of the inert aerosol tests of the aged units were performed at the same airflow rate, which was the maximum flow rate the units would likely encounter in actual use. The pressure drops of the devices were also evaluated at the test flow rate. A complete listing of the results from these evaluations for each air cleaner is provided in Appendix G. A summary of the results is provided for the filters and EACs in the following sections.

4.3.1 Aging Evaluations – Filters

Table 4-5 summarizes the results from the filter aging evaluations. Figures 4-31 through 4-44 provide graphic illustrations of the test results. It should be noted that individual filters were evaluated at each of the different loading durations, so some of the variation in the pressure drops and collection efficiencies can be attributed to the variability in the performance of individual filters. For the two electrostatic residential filters (6DDUE-8 and 8NM-10), the collection efficiency for larger particles (3.0 to 10.0 µm) either increased significantly (6DDUE-8) or remained the same (8NM-10) after the filters started to be loaded with particles. However, for both filters, a substantial decrease in collection efficiency was noted for smaller particles (0.3 to 3 µm) after the filters were loaded. The collection efficiency of the filters for smaller particles did not exceed the initial efficiency until between 8 and 12 weeks of loading had occurred. The pressure drops of both residential filters remained fairly consistent through the first 8 weeks of use but then increased greatly between weeks 8 and 12. It should be noted that 12 weeks of use constitutes 100% of the manufacturer-recommended service time for these two filters.

Table 4-5. Summary of the Results from the Filter Aging Evaluations

Filter	Description	Electrostatic	MERV Rating (literature)	MERV Rating from testing (Hours of HVAC Operation)	Average Collection Efficiencies (%) E1 0.3–1.0 µm	E2 1.0–3.0 µm	E3 3.0–10 µm	Approximate Mass of Dust Collected (grams)	Literature Pressure Drop (in. w.g.)	Measured Pressure Drop (in. w.g.)	Notes
6DDUE–8	Pleated electet (residential)	Yes	8	7 (0 weeks – 0 hours)	20.6	51.9	56.8	0	0.17 at 295 fpm	0.14 at 295 fpm (0 weeks)	NA
				8 (2 weeks – 199 hours)	7.3	25.8	75.3	1		0.16 at 295 fpm (2 weeks)	
				9 (4 weeks – 544 hours)	12.1	38.3	87.6	8		0.23 at 295 fpm (4 weeks)	
				7 (8 weeks – 1,040 hours)	4.5	35.6	67.2	7		0.19 at 295 fpm (8 weeks)	
				10 (12 weeks – 1,307 hours)	11.0	64.5	93.2	5		0.26 at 295 fpm (12 weeks)	
8NM–10	Pleated electrostatic (residential)	Yes	10	12 (0 weeks – 0 hours)	31.2	82.4	91.4	0	NA	0.43 at 295 fpm (0 weeks)	NA
				10 (2 weeks – 250 hours)	19.5	59.3	92.1	2		0.50 at 295 fpm (2 weeks)	
				11 (4 weeks – 450 hours)	27.2	66.6	93.8	1		0.58 at 295 fpm (4 weeks)	
				11 (8 weeks – 892 hours)	18.1	69.4	91.2	3		0.49 at 295 fpm (8 weeks)	
				13 (12 weeks – 1,272 hours)	65.6	90.9	93.4	9		1.75 (12 weeks)	

Table 4–5. Summary of the Results from the Filter Aging Evaluations (Continued)

Filter	Description	Electrostatic	MERV Rating (literature)	MERV Rating from testing (Hours of HVAC Operation)	Average Collection Efficiencies (%)			Approximate Mass of Dust Collected (grams)	Literature Pressure Drop (in. w.g.)	Measured Pressure Drop (in. w.g.)	Notes
C17FPP–8	Pleated electrostatic prefilter (commercial)	Yes	8	7 (0 weeks – 0 hours) – 12 x 24 x 2	39.1	75.5	64.7	0	0.30 at 500 fpm	0.55 at 492 fpm (0 weeks)	None
				8 (0 weeks – 0 hours)	48.3	91.1	81.3	0		0.44 at 492 fpm (0 weeks)	
				8 (2 weeks – 336 hours)	4.7	27.3	70.8	8		0.45 at 492 fpm (2 weeks)	
				8 (4 weeks – 672 hours)	4.7	25.6	72.5	20		0.45 at 492 fpm (4 weeks)	
				8 (8 weeks – 1,344 hours)	8.6	31.0	75.8	38		0.47 at 492 fpm (8 weeks)	
				8 (16 weeks – 2,688 hours)	3.8	30.3	74.9	82		0.57 at 492 fpm (16 weeks)	
C15AAA–11	Pleated electrostatic prefilter (commercial)	Yes	11	8 (0 weeks – 0 hours) – 12 x 24 x 2	47.5	72.9	71.4	0	0.38 at 500 fpm	0.40 at 492 fpm (0 weeks)	Collection efficiency was well below expected values.
				7 (0 weeks – 0 hours)	41.1	71.9	66.6	0		0.34 at 492 fpm (0 weeks)	
				7 (2 weeks – 336 hours)	11.0	26.8	66.0	13		0.37 at 492 fpm (2 weeks)	
				7 (4 weeks – 672 hours)	10.3	25.3	62.0	24		0.38 at 492 fpm (4 weeks)	
				7 (8 weeks – 1,344 hours)	3.3	21.7	63.6	42		0.39 at 492 fpm (8 weeks)	
				7 (16 weeks – 2,688 hours)	6.3	26.0	66.7	89		0.46 at 492 fpm (16 weeks)	

Table 4-5. Summary of the Results from the Filter Aging Evaluations (Continued)

Filter	Description	Electrostatic	MERV Rating (literature)	MERV Rating from testing (Hours of HVAC Operation)	Average Collection Efficiencies (%)			Approximate Mass of Dust Collected (grams)	Literature Pressure Drop (in. w.g.)	Measured Pressure Drop (in. w.g.)	Notes
C8GZ-13	Pleated synthetic box filter (commercial)	Yes	13	12 (0 weeks – 0 hours)	69.4	88.3	98.6	0	0.44 at 500 fpm	0.59 at 492 fpm (0 weeks)	Collection efficiency degraded over entire aging period.
				11 (2 weeks – 336 hours)	46.0	73.3	96.6	9		0.59 at 492 fpm (2 weeks)	
				11 (4 weeks – 672 hours)	38.7	68.2	96.2	14		0.57 at 492 fpm (4 weeks)	
				11 (8 weeks – 1,344 hours)	34.6	65.3	95.9	32		0.57 at 492 fpm (8 weeks)	
				10 (16 weeks – 2,688 hours)	27.5	53.7	89.8	50		0.58 at 492 fpm (16 weeks)	
C14PCS	Pleated microfiberglass (commercial)	No	14[B]	12 (0 weeks – 0 hours)	71.3	89.4	98.6	0	0.60 at 500 fpm	0.60 at 492 fpm (0 weeks)	Collection efficiency was very consistent during entire test period.
				14 (2 weeks – 336 hours)	79.0	92.5	99.4	17		0.62 at 492 fpm (2 weeks)	
				13 (4 weeks – 672 hours)	73.2	90.3	98.6	26		0.62 at 492 fpm (4 weeks)	
				14 (8 weeks – 1,344 hours)	78.1	91.9	98.7	39		0.64 at 492 fpm (8 weeks)	
				14 (16 weeks – 2,688 hours)	83.8	97.3	99.3	76		0.66 at 492 fpm (16 weeks)	
C11GM-1	95% DOP Pleated microfiberglass (commercial)	No	16	16 (0 weeks – 0 hours)	98.6	99.9	100	0	0.61 at 500 fpm	0.85 at 492 fpm (0 weeks)	Collection efficiency was very consistent during entire test period.
				16 (2 weeks – 336 hours)	98.5	99.9	100	11		0.84 at 492 fpm (2 weeks)	
				16 (4 weeks – 672 hours)	98.7	99.9	100	22		0.83 at 492 fpm (4 weeks)	
				16 (8 weeks – 1,344 hours)	98.7	99.9	99.9	42		0.83 at 492 fpm (8 weeks)	
				16 (16 weeks – 2,688 hours)	99.2	100	100	81		0.86 at 492 fpm (16 weeks)	

[B] – MERV rating based on Table E-1 in ASHRAE 52.2-1999

Figure 4-31. Measured Collection Efficiency of Residential Filter 6DDUE-8 During the Aging Evaluations

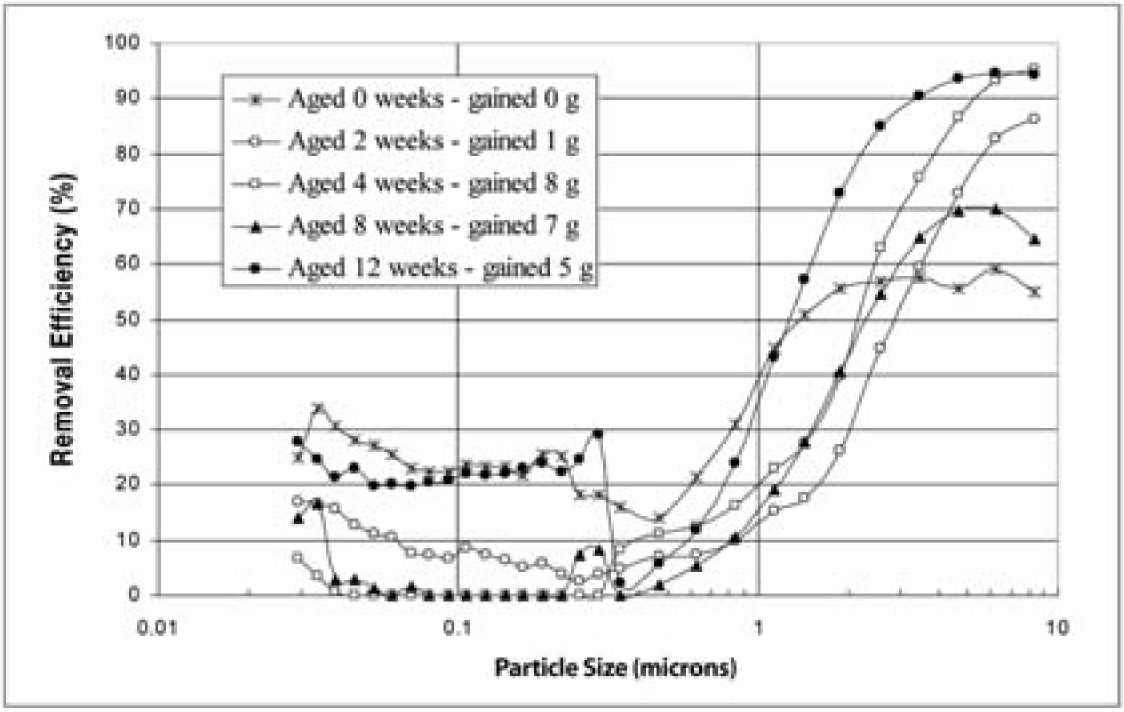


Figure 4-32. Measured Pressure Drop of Residential Filter 6DDUE-8 During the Aging Evaluations

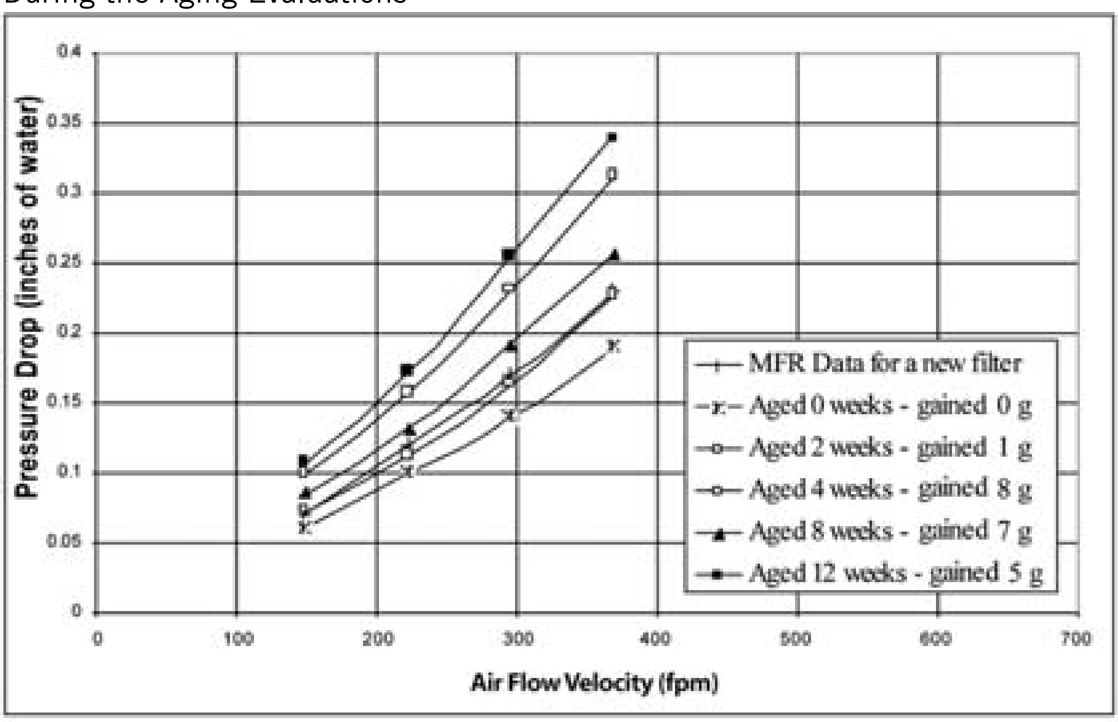


Figure 4-33. Measured Collection Efficiency of Residential Filter 8NM-10 During the Aging Evaluations

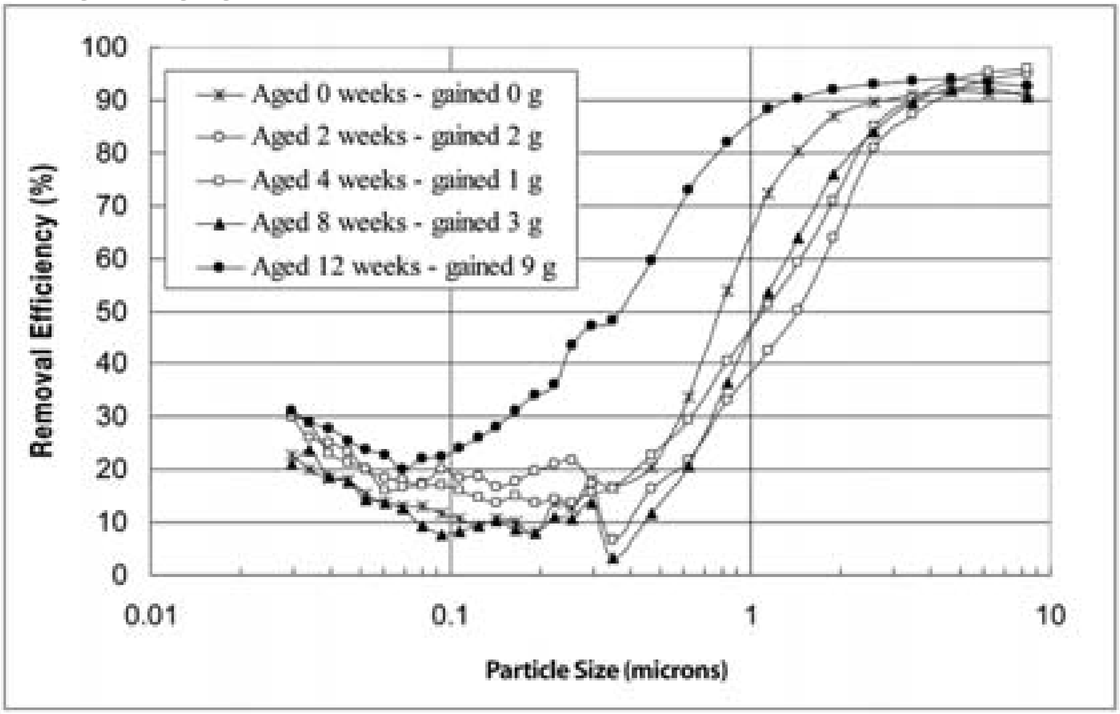


Figure 4-34. Measured Pressure Drop of Residential Filter 8NM-10 During the Aging Evaluations

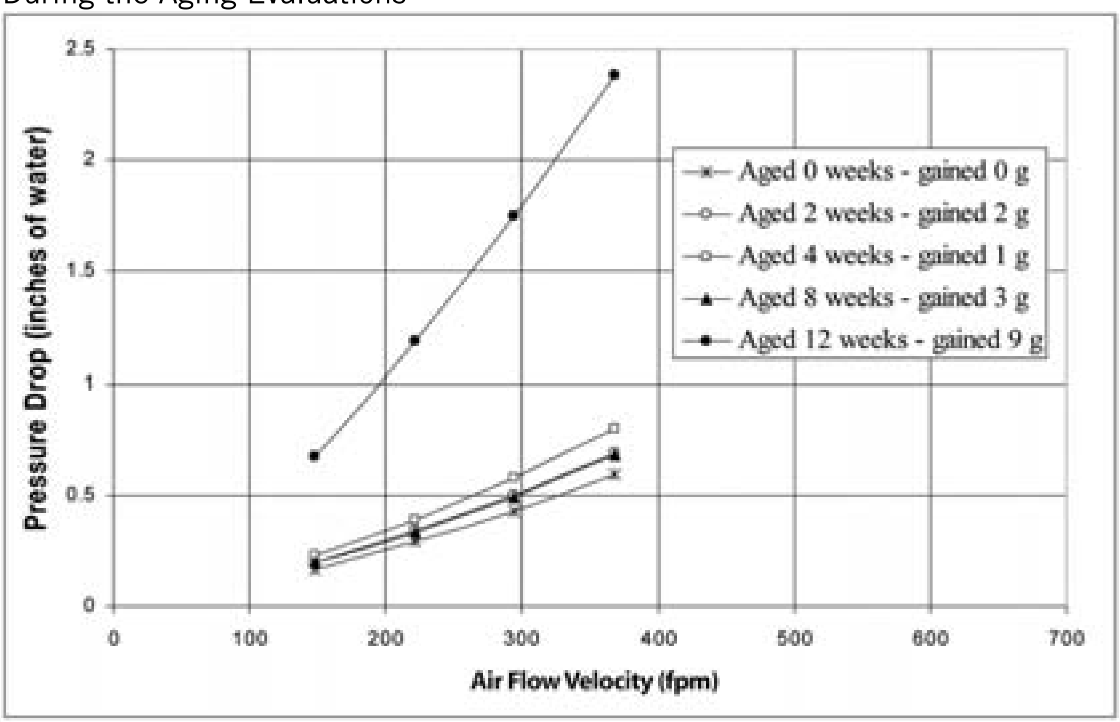


Figure 4-35. Measured Collection Efficiency of Commercial Filter C17FPP-8 During the Aging Evaluations

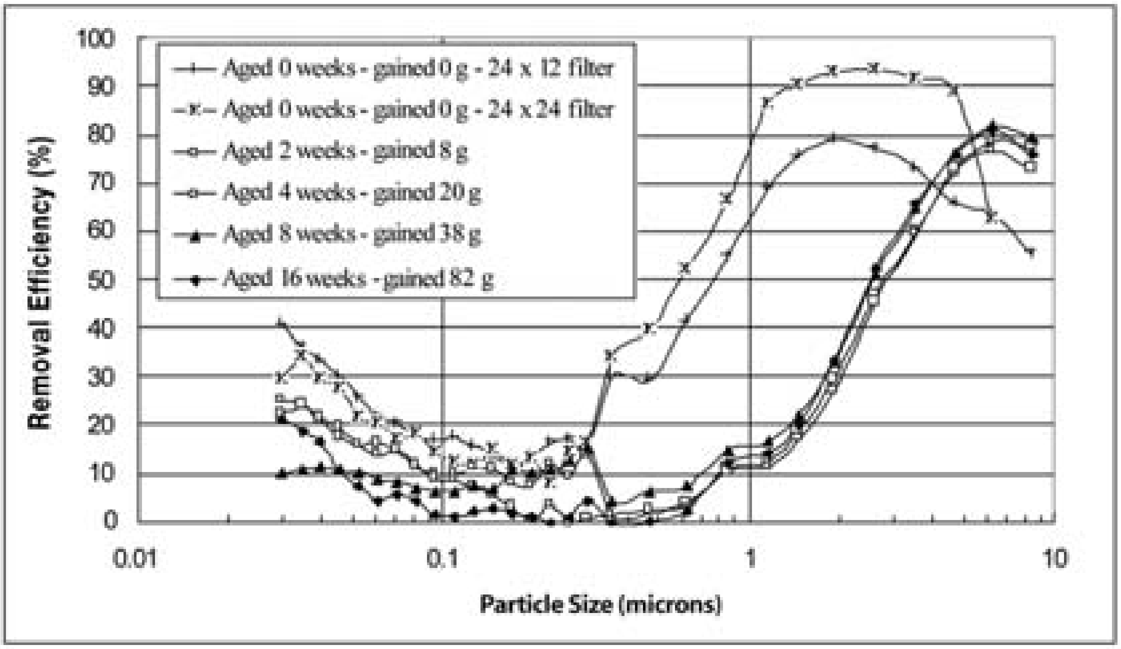


Figure 4-36. Measured Pressure Drop of Commercial Filter C17FPP-8 During the Aging Evaluations

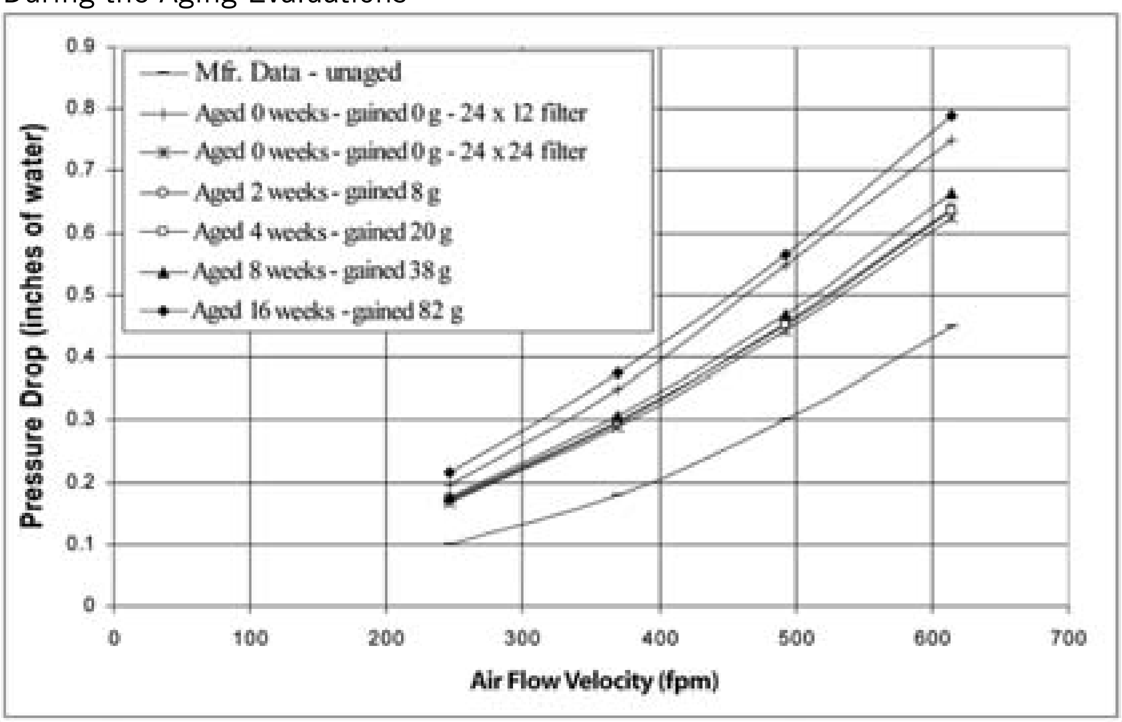


Figure 4-37. Measured Collection Efficiency of Commercial Filter C15AAA-11 During the Aging Evaluations

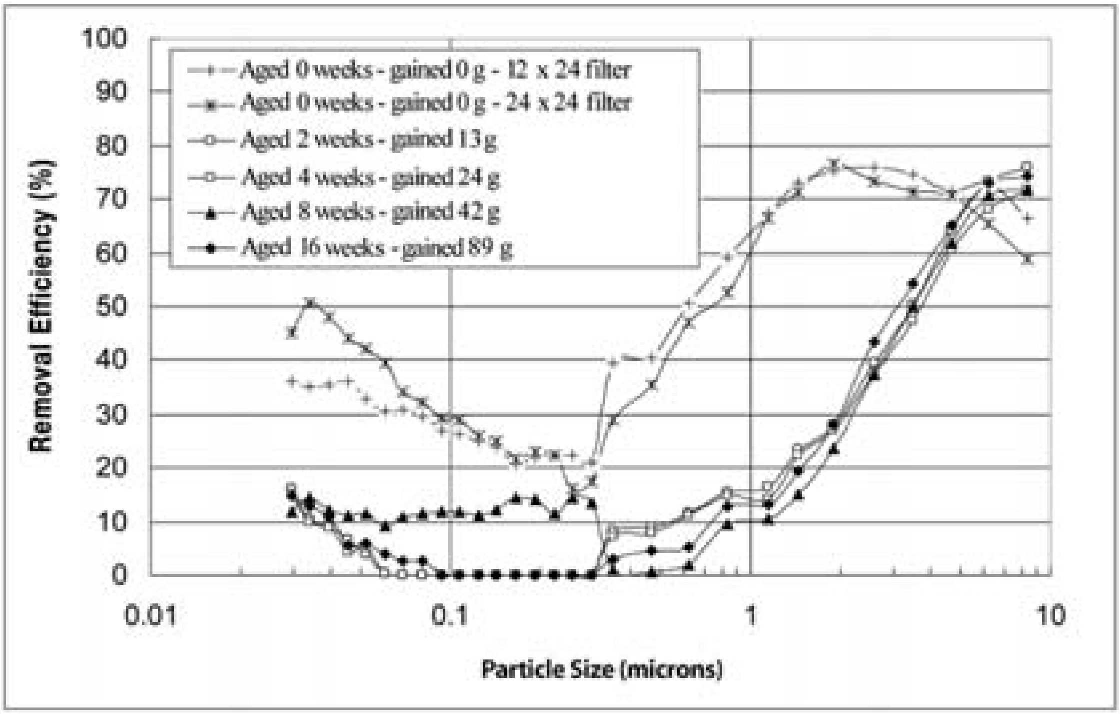


Figure 4-38. Measured Pressure Drop of Commercial Filter C15AAA-11 During the Aging Evaluations

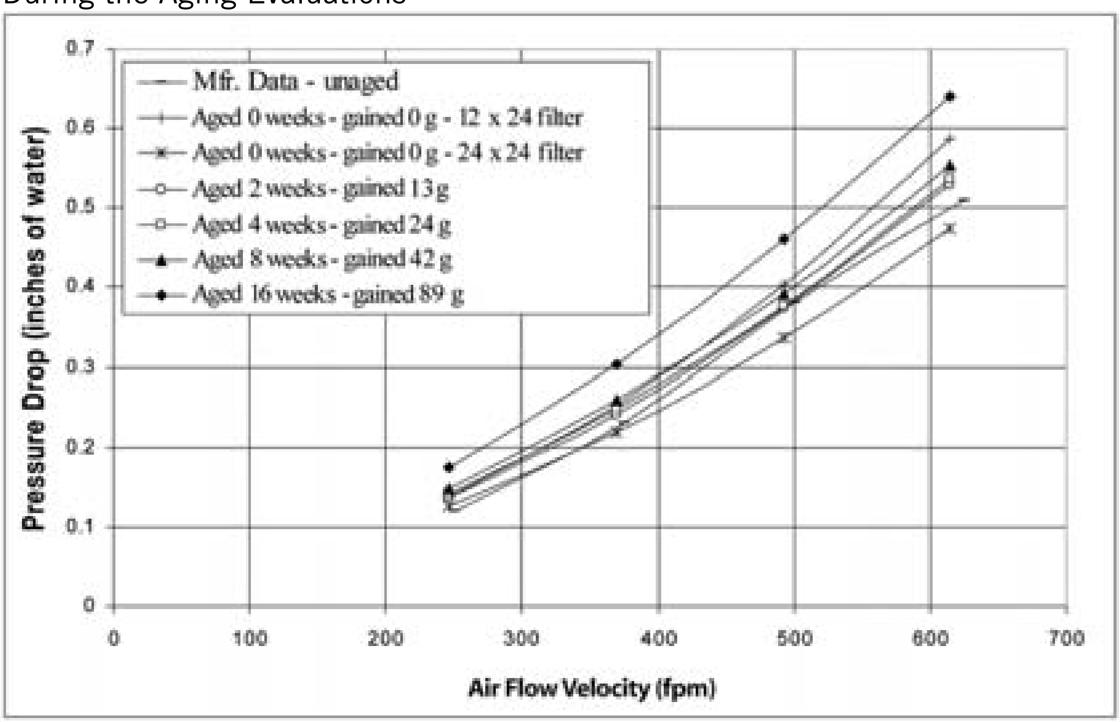


Figure 4-39. Measured Collection Efficiency of Commercial Filter C8GZ-13 During the Aging Evaluations

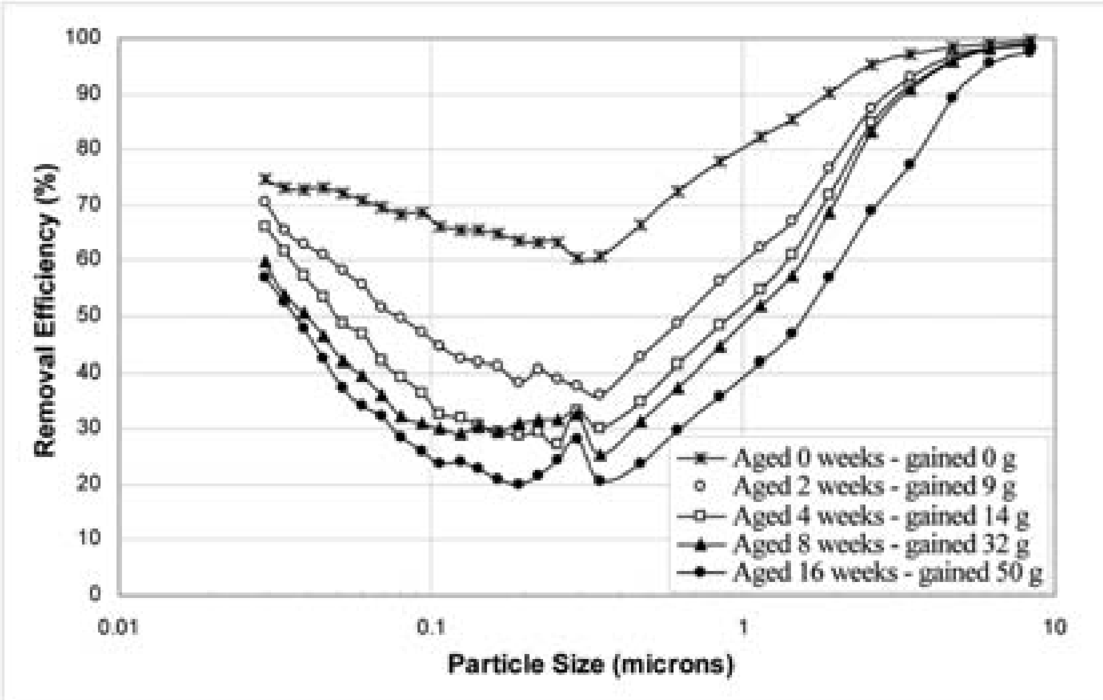


Figure 4-40. Measured Pressure Drop of Commercial Filter C8GZ-13 During the Aging Evaluations

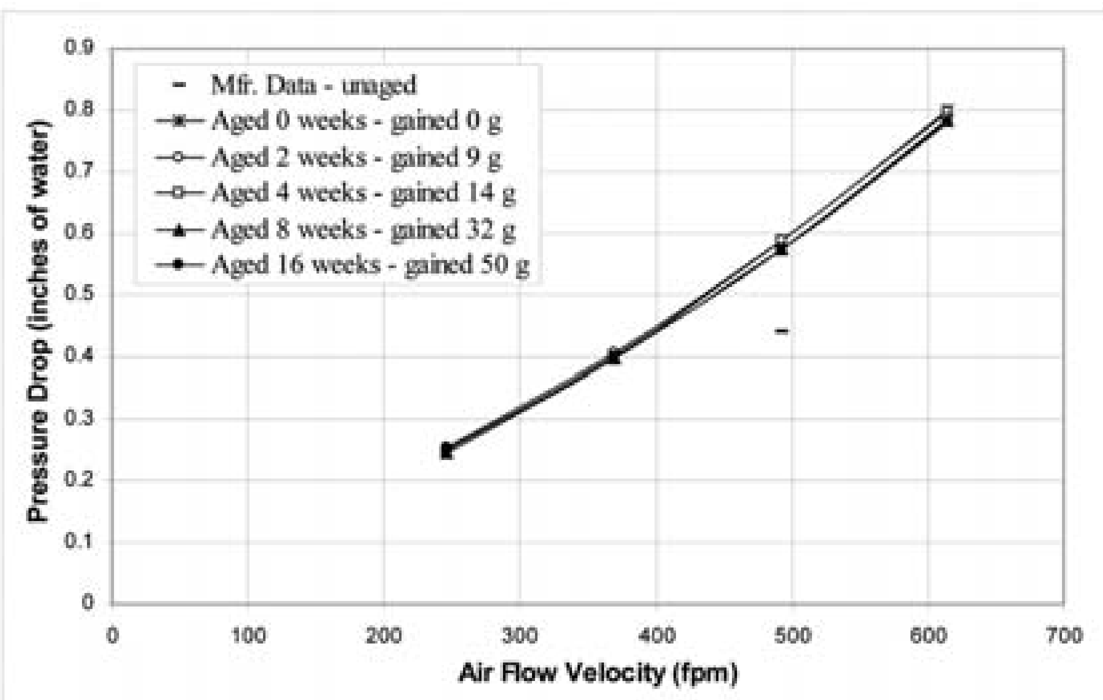


Figure 4-41. Measured Collection Efficiency of Commercial Filter C14PCS During the Aging Evaluations

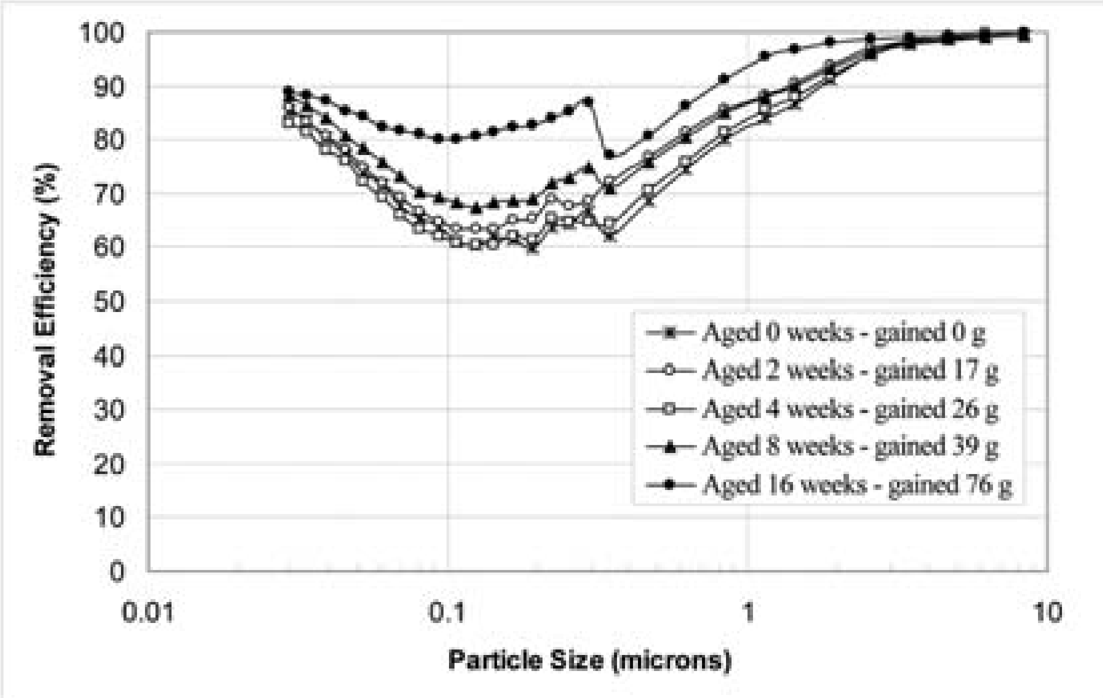


Figure 4-42. Measured Pressure Drop of Commercial Filter C14PCS During the Aging Evaluations

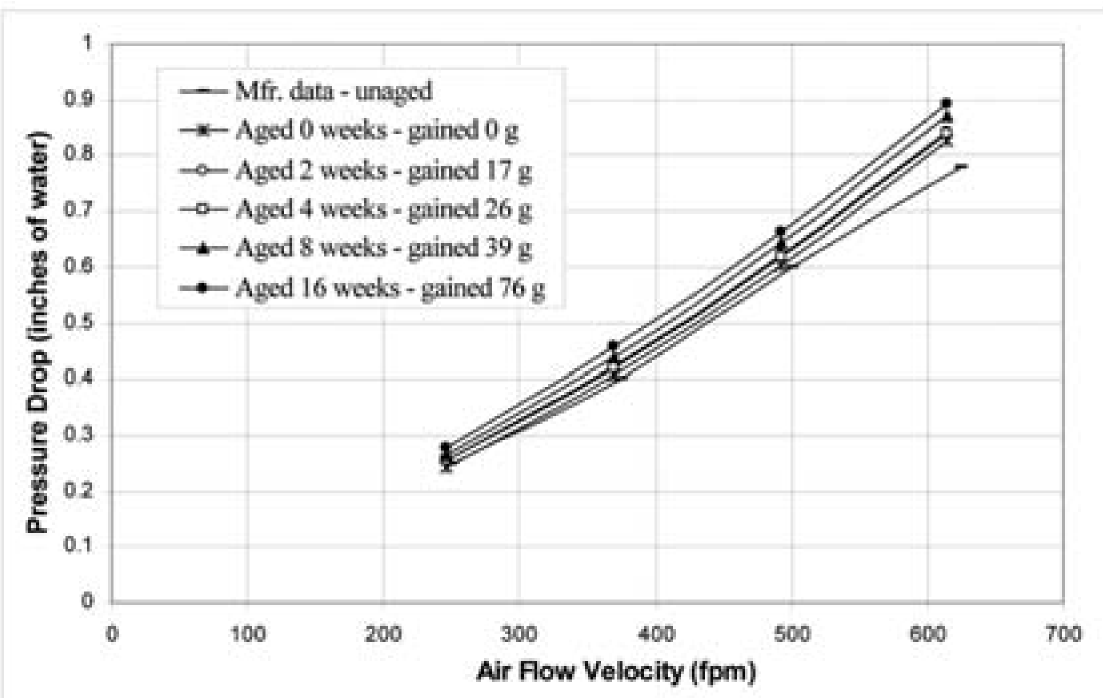


Figure 4-43. Measured Collection Efficiency of Commercial Filter C11GM-16 During the Aging Evaluations

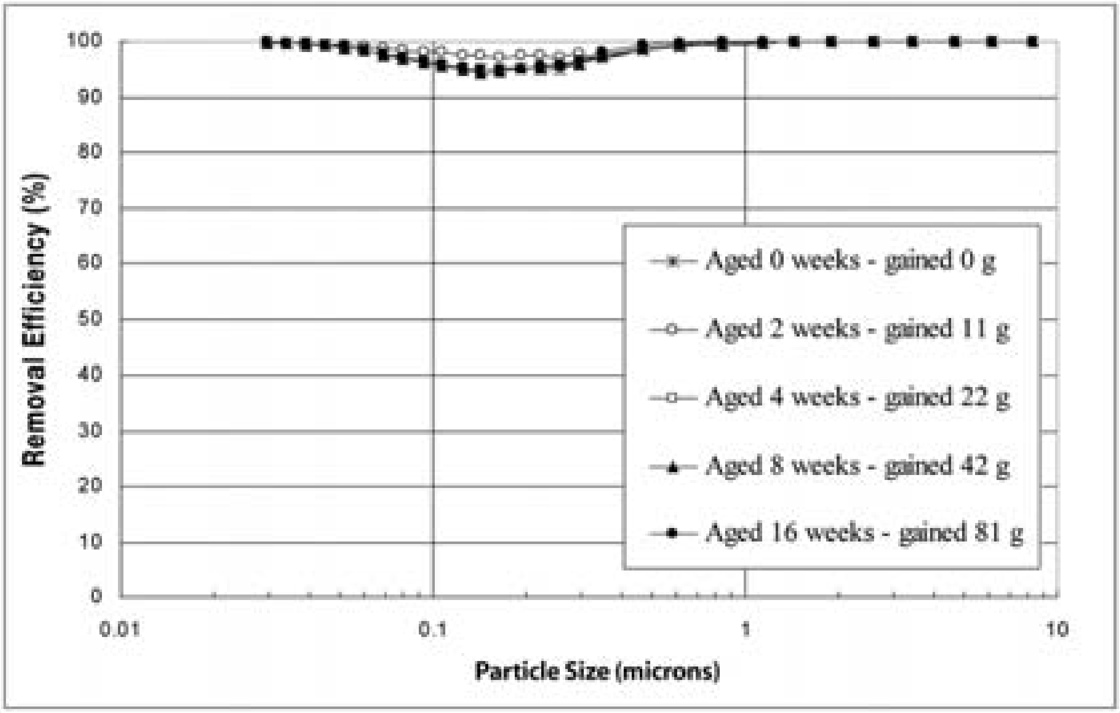
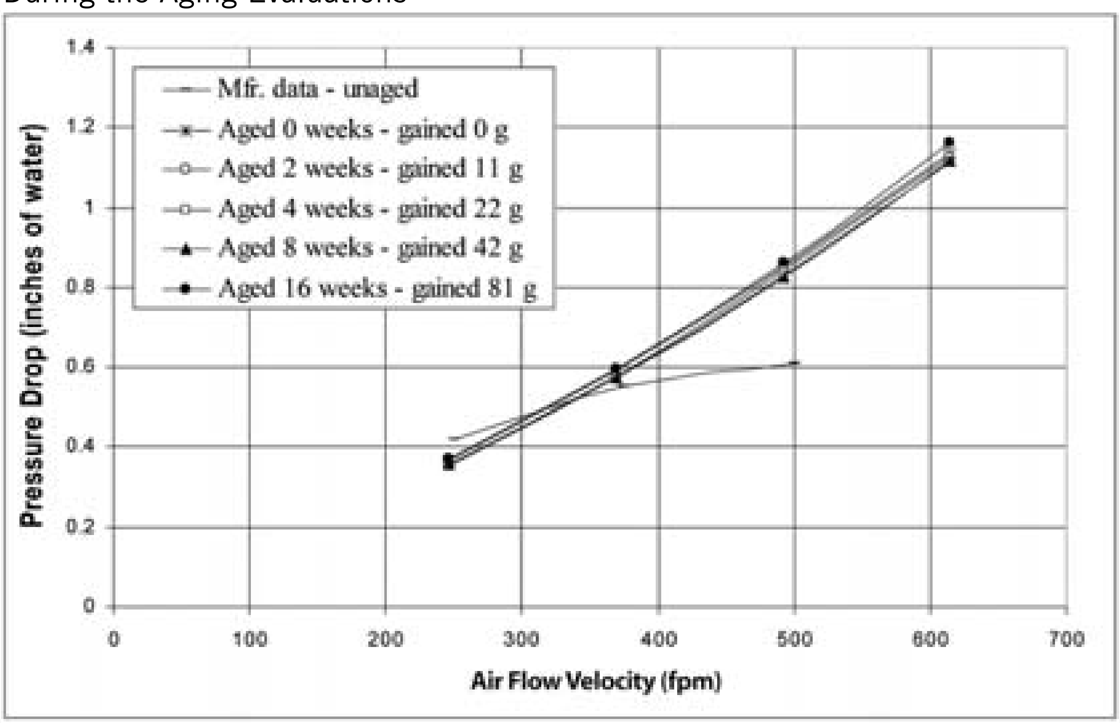


Figure 4-44. Measured Pressure Drop of Commercial Filter C11GM-16 During the Aging Evaluations



The two electrostatic commercial prefilters (C17FPP-8 and C15AAA-11) demonstrated consistent average collection efficiencies over the entire 16-week aging duration for larger particles (4.0 to 10.0 µm). However, as can be seen in Figures 4-35 and 4-37, the shape of the collection efficiency curve for the unloaded filters (0 week) differed from the shape of the curve for the loaded filters. The shape of the 0 week collection efficiency curves is not unusual for unloaded filters, although it is generally more frequently observed with lower-efficiency filters (see Figures 4-1, 4-3, 4-5, 4-21, and 4-31 for examples). As with the residential electrostatic filters, there was a very substantial drop in collection efficiency for particles smaller than approximately 4 µm once the loading began, and the collection efficiency for the smaller particles never returned to the measured initial values. The pressure drops of the prefilters did not demonstrate any noticeable increase over the aging period. It should be noted that the typical service life for prefilters in the HVAC system of interest ranges from 3 to 6 months, so the 4 months of aging that was performed represented between 67% and 133% of a typical service period. It should also be noted that the performance of filter C15AAA-11 was considerably poorer than was expected from the manufacturers' literature.

In contrast, the 12-inch deep electrostatic commercial box filter (C8GZ-13) substantially degraded in collection efficiency for all particle sizes over the entire aging period, dropping steadily from MERV 12 to MERV 10. No change in pressure drop occurred over this period, implying that a suitable dust cake did not form during loading, which would likely have caused the degradation of collection efficiency to slow. It should be noted that the typical service life for filter C8GZ-13 in the application of interest is 6 to 12 months, typically closer to 12 months, so the aging period represented only 33% to 67% of the typical service life.

As expected, the two commercial, 12-inch deep, non-electrostatic, traditional fiberglass media deep-pleated filters (C14PCS and C11GM-16) did not demonstrate any degradation in collection efficiency during the aging period. In fact, the collection efficiency of C14PCS clearly increased as dust was collected on the filter during aging. No change in pressure drop was noted over the aging period for these two filters. The typical service life for these two filters in the application of interest is 6 to 12 months, typically closer to 12 months, so the aging period represented only 33% to 67% of the typical service life.

4.3.2 Aging Evaluations – Electronic Air Cleaners

Table 4-6 summarizes the results from the EAC aging evaluations. Figures 4-45 through 4-50 provide graphic illustrations of the test results. In contrast to the filter aging, a single EAC was evaluated over the aging period, eliminating the contribution of unit variation into the measured pressure drops and collection efficiencies. It should be noted that no cleaning was performed over the entire aging duration. This was consistent with the manufacturer's recommendations of cleaning intervals between 1 and 6 months in duration. (In general, according to the manufacturer's literature, cleaning was recommended only when a visible inspection indicated that cleaning is clearly required.)

The pressure drops of all three units remained consistent over the entire aging period, demonstrating neither significant changes nor any discernable pattern. Unit A appeared to demonstrate a small drop in collection efficiency between 336 hours and 1,008 hours of use, as it dropped from a MERV 15 to a MERV 14, but it should be noted that this was due to a minor decrease in the average efficiency for 0.3 to 1 µm particles (from 87.6% to 83.2%), as the efficiencies in the other particle size ranges were virtually identical. The average efficiency for 0.3 to 1 µm particles for Unit A decreased slightly again between 1,008 and 2,016 hours (from 83.2% to 80.7%), but again the efficiencies in the other particle size ranges were virtually identical. By far, Unit A demonstrated the least degradation in performance over the aging period and appeared to be operating satisfactorily even after 2,016 hours of use without any maintenance.

Unit H also performed reasonably well over the aging period but showed more degradation than Unit A between 336 and 1,008 hours of aging, even though its MERV rating did not change. Its average efficiency for 0.3 to 1 µm particles decreased from 93.4% to 86.8% between 336 and 1,008 hours of operation. As shown in Figure 4-47, the MERV rating for Unit H decreased to 12 after 2,016 hours of operation, corresponding to a decrease in average efficiency for 0.3 to 1 µm particles from 86.8% to 74.7%, as well as decreases for larger particles. Cleaning of Unit H after 84 days of continuous operation appeared to be warranted.

In contrast, Unit P decreased slightly in collection efficiency for particles smaller than 1 µm between 168 and 336 hours of use, and then dropped precipitously from a MERV 14 to a MERV 6 between 336 hours and 1,008 hours of use. Despite the significant drop in collection efficiency for Unit P between 336 hours and 1,008 hours, the visible buildup on the unit was not substantial enough to warrant cleaning. Unit P was not visibly dirtier than the other two units, so the user would have no reason to suspect that performance had substantially degraded. However, based on its collection efficiency, cleaning of Unit P would be recommended after 14 days of continuous use.

Table 4-6. Summary of the Results from the Electronic Air Cleaner Aging Evaluations

Unit	MERV Rating (literature)	MERV Rating (testing)	Average Collection Efficiencies (%)			Literature Pressure Drop (in. w.g.)	Measured Pressure Drop (in. w.g.)	Notes
			E1 0.3-1.0 μm	E2 1.0-3.0 μm	E3 3.0-10 μm			
A	> 94% at 0.35 μm (MERV 15)	14 (aged 0 hours)	84.2	93.1	97.9	0.17 at 500 fpm	0.12 at 295 fpm	None
		15 (aged 168 hours)	88.3	94.5	97.3		0.16 at 295 fpm	
		15 (aged 336 hours)	87.6	94.8	98.2		0.12 at 295 fpm	
		14 (aged 1,008 hours)	83.2	93.6	96.8		0.16 at 295 fpm	
		14 (aged 2,016 hours)	80.7	93.8	96.8		0.15 at 295 fpm	
H	Up to MERV 12 at 492 fpm	15 (aged 0 hours)	92.7	96.9	98.1	0.06 at 295 fpm	0.11 at 295 fpm	None
		15 (aged 168 hours)	92.6	97.3	98.3		0.09 at 295 fpm	
		15 (aged 336 hours)	93.4	97.2	98.2		0.13 at 295 fpm	
		15 (aged 1,008 hours)	86.8	95.6	98.1		0.13 at 295 fpm	
		12 (aged 2,016 hours)	74.7	89.4	94.6		0.13 at 295 fpm	
P	NA	14 (aged 0 hours)	84.0	95.1	97.1	0.11 at 500 fpm	0.06 at 295 fpm	None
		14 (aged 168 hours)	82.3	94.7	97.6		0.05 at 295 fpm	
		14 (aged 336 hours)	78.5	93.2	96.8		0.05 at 295 fpm	
		6 (aged 1,008 hours)	18.4	27.7	46.8		0.07 at 295 fpm	
		5 (aged 2,016 hours)	4.1	5.6	21.8		0.06 at 295 fpm	

Figure 4-45. Measured Collection Efficiency of Electronic Air Cleaner A During the Aging Evaluations

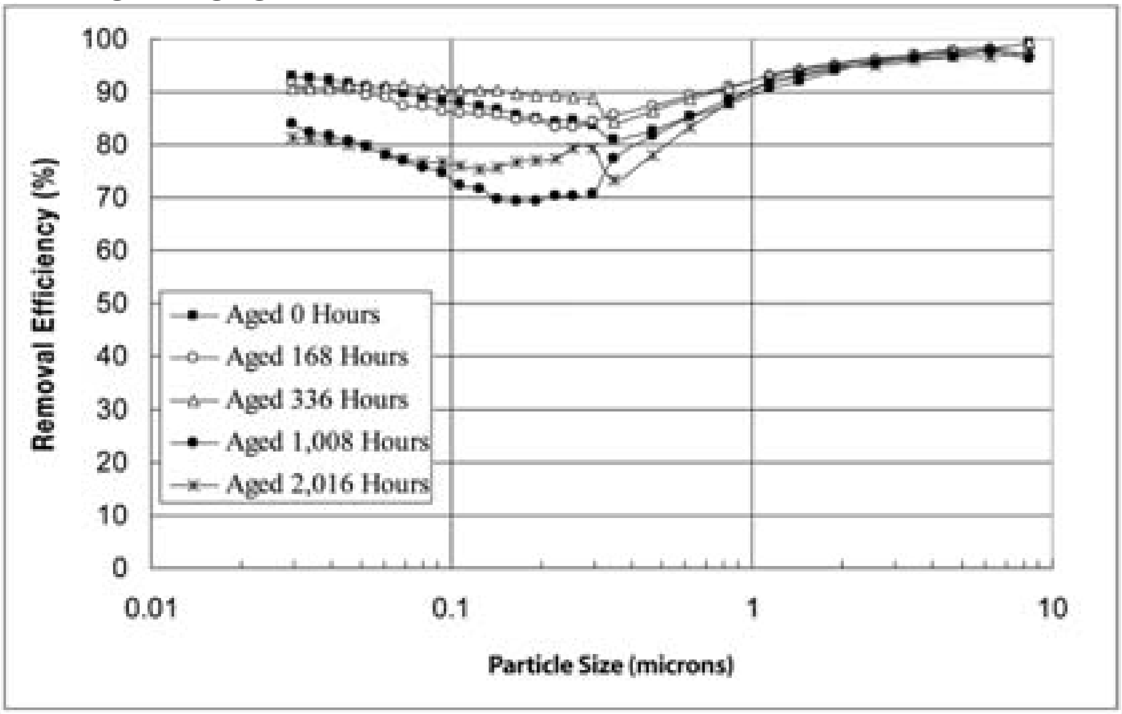


Figure 4-46. Measured Pressure Drop of Electronic Air Cleaner A During the Aging Evaluations

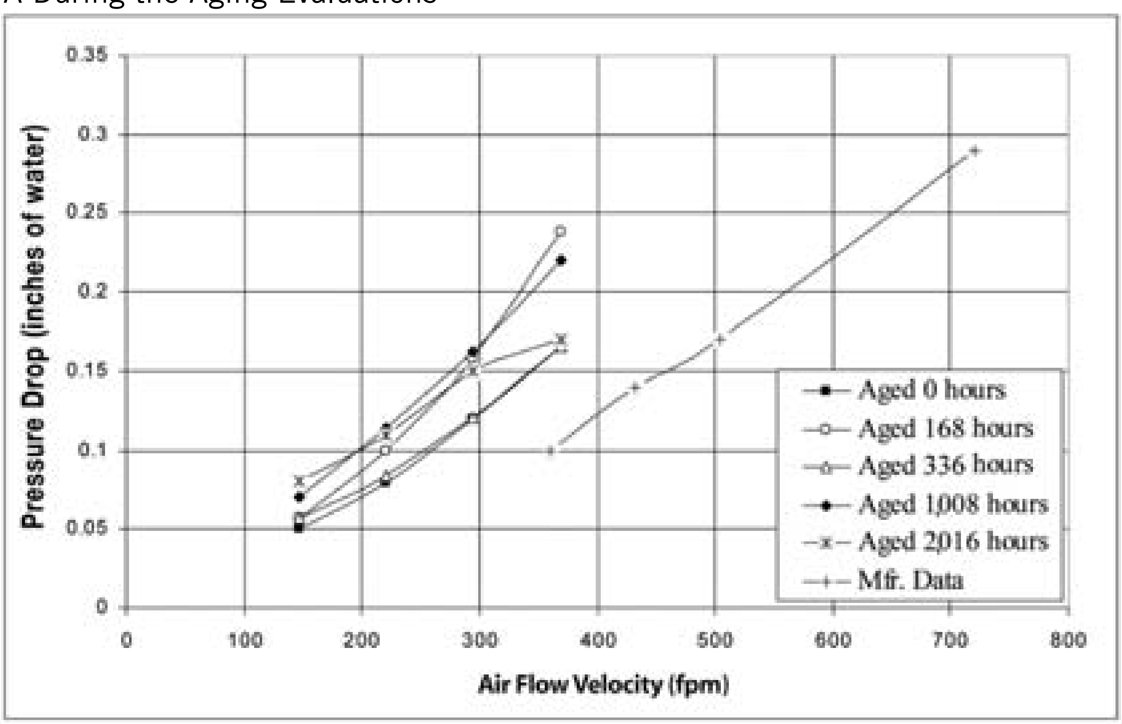


Figure 4-47. Measured Collection Efficiency of Electronic Air Cleaner H During the Aging Evaluations

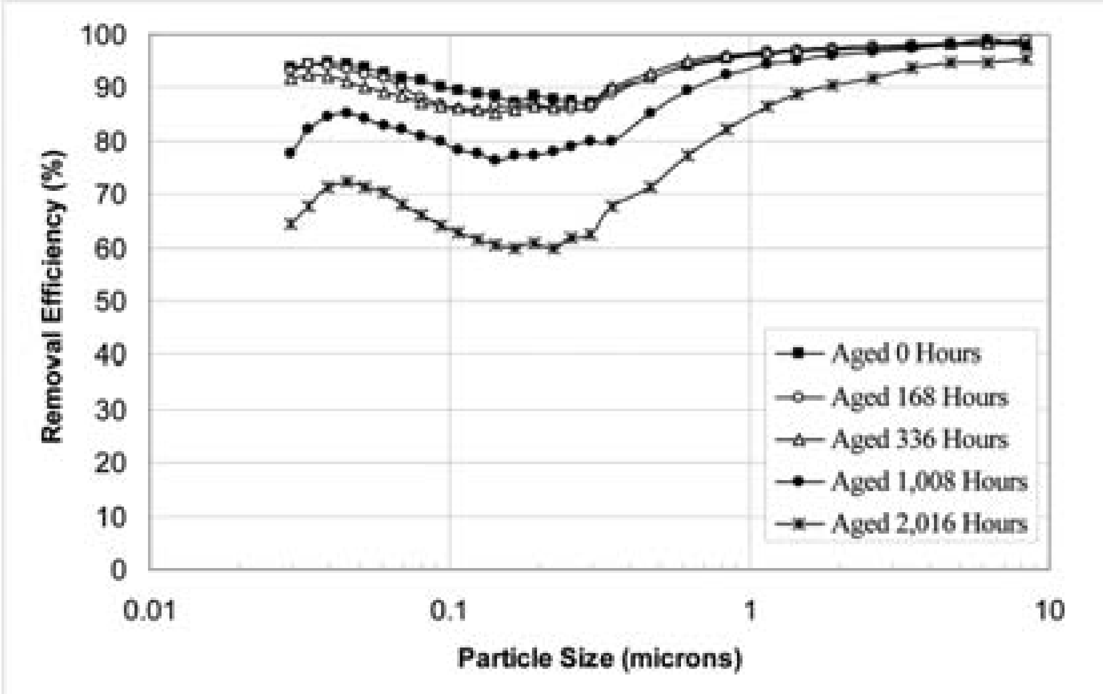


Figure 4-48. Measured Pressure Drop of Electronic Air Cleaner H During the Aging Evaluations

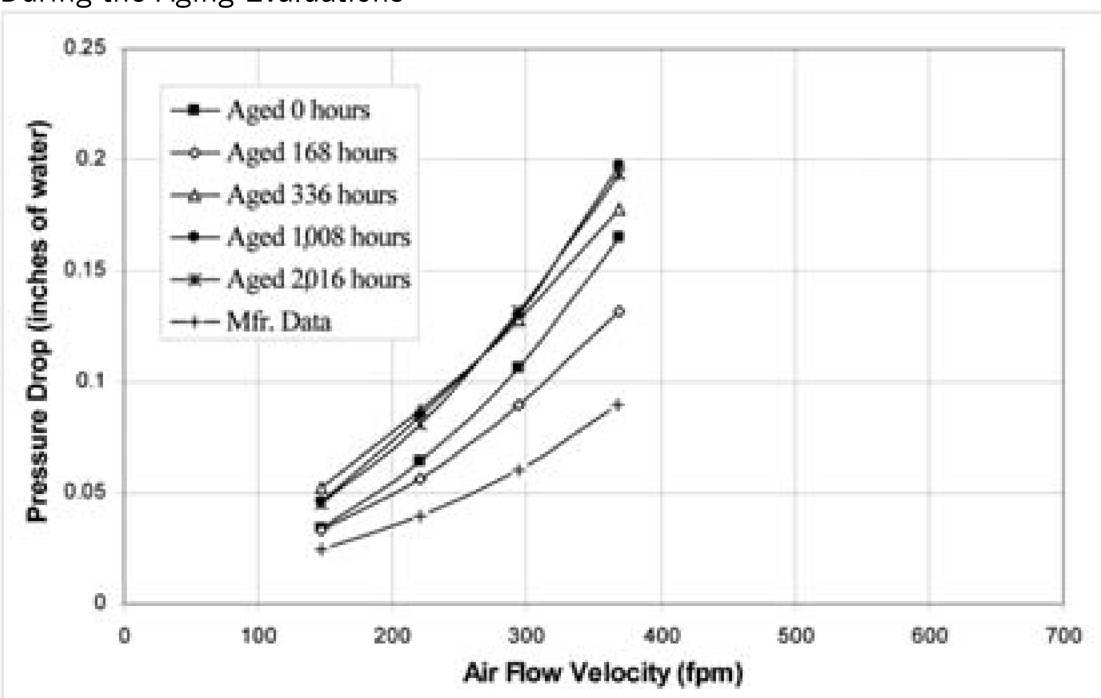


Figure 4-49. Measured Collection Efficiency of Electronic Air Cleaner P During the Aging Evaluations

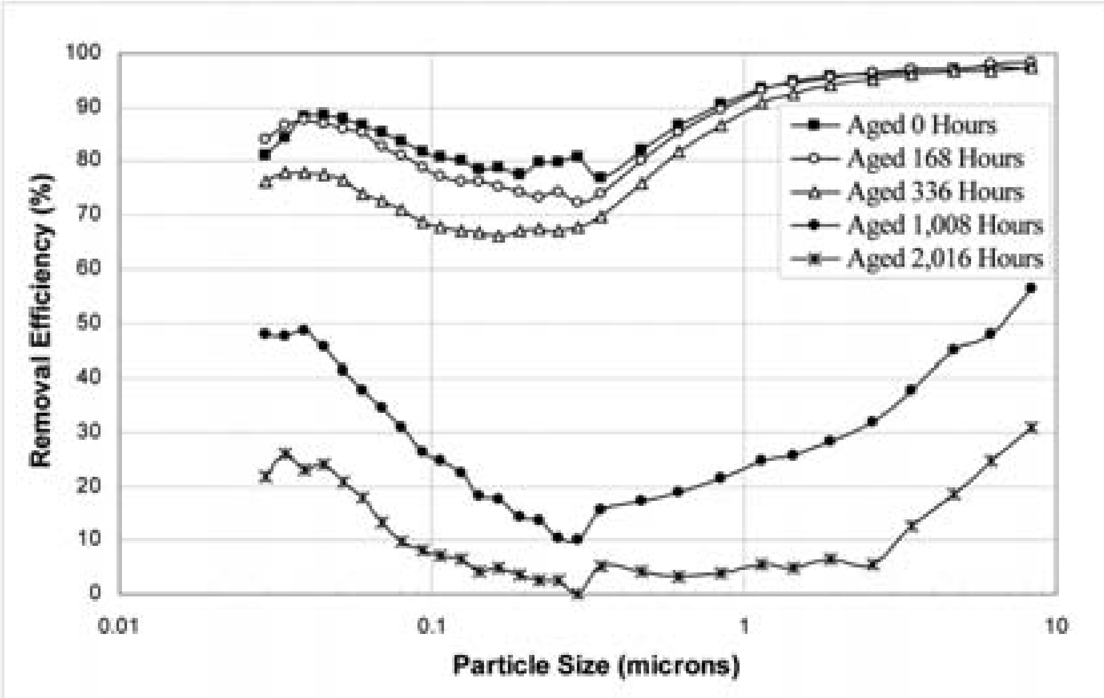
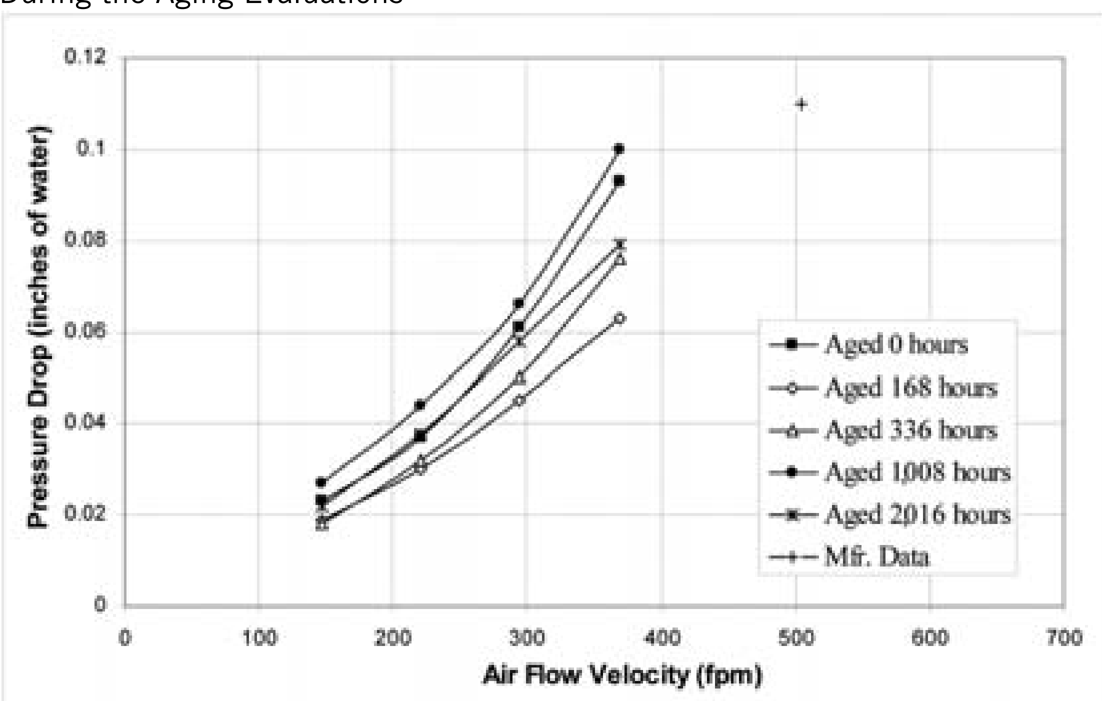


Figure 4-50. Measured Pressure Drop of Electronic Air Cleaner P During the Aging Evaluations



4.4 Results from the Conditioning Evaluations

As described in Section 3.4, eight electrostatic filters were evaluated using a modified inert aerosol test method (Section 3.1) that involved conditioning to identify their minimum collection efficiency, rather than their initial collection efficiency. This modified inert aerosol test method was performed in accordance with the latest recommendation from ASHRAE, namely draft Addendum C for ANSI/ASHRAE Standard 52.2-1999.

Similarly, as described in Section 3.5, three EACs were evaluated by the inert aerosol methods described in Section 3.1 both before and after exposure to silicon vapor. The purpose of the exposure to silicon vapor was to compare the results from exposure to silicon vapor to the results from the "in-use" tests to determine whether the silicon vapor exposure resulted in a realistic assessment of the EACs' likely performance after one month of actual use.

All of the inert aerosol tests of the conditioned units were performed at the same airflow rate, which was the maximum flow rate the units would likely encounter in actual use. The pressure drops of the devices were also evaluated at the test flow rate. A complete listing of the results from these evaluations for each air cleaner is provided in Appendix H. A summary of the results is provided for the filters and EACs in the following sections.

4.4.1 Results from the Conditioning Evaluations – Filters

As discussed in Section 3.4, eight electrostatic filters were evaluated before, during, and after a series of conditioning steps. The conditioning was performed according to draft Addendum C for ASHRAE 52.2-1999, which is aimed at developing a repeatable test method for evaluating the performance of electrostatic filters in actual use. (Electrostatic filters are generally known to decrease in collection efficiency when initially loaded and to continue this decrease until the dust cake that builds up is sufficient to counteract the decrease in the efficiency of electrostatic attraction as the available surface area on the filter fibers decreases.) As discussed in Section 3.4, the test method consisted of multiple collection efficiency evaluations between loadings with submicron potassium chloride particles. A summary of the results is provided in Table 4-7. Illustrations of the results are provided in Figures 4-51 through 4-63. For the convenience of the reader, charts of selected results from the aging evaluations are included in Figures 4-51 through 4-63 to allow a direct comparison.

As shown in Figure 4-51, for residential filter 6DDUE-8, upon conditioning, the collection efficiency increased significantly for particles larger than 1 µm but appeared to decrease slightly for particles smaller than 1 µm. This was consistent with the observations during the aging tests shown in Figure 4-52, in which the collection efficiency increased upon aging for particles larger than 4 µm but decreased significantly for particles smaller than 2 µm, until approximately 12 weeks of aging had occurred. Residential filters 5RM-11-1, 4FUA-12-3, and 7AST-8-3, for which there are no aging test results to compare, behaved similarly to filter 6DDUE-8. As shown in Figures 4-53, 4-54, and 4-55, upon conditioning, the collection efficiency of all three residential filters increased for particles larger than approximately 1 to 2 µm but either decreased slightly or remained essentially constant during the entire conditioning process.

As shown in Figure 4-56, for residential filter 8NM-10, the collection efficiency decreased slightly for all particles upon initial conditioning but increased for all particles once the equivalent of 1 month of conditioning had been performed. This is similar to the results observed during the aging tests shown in Figure 4-57, although the decrease was more substantial and required approximately 12 weeks of aging to increase past the initial values.

Table 4-7. Summary of the Results from the Filter Conditioning Evaluations

Filter	Description	MERV Rating (literature)	MERV Rating from testing (CT[a])	Average Collection Efficiencies (%)			Approximate Months of Use Simulated	Literature Pressure Drop (in. w.g.)	Measured Pressure Drop (in. w.g.)	Notes
				E1 0.3-1.0 μm	E2 1.0-3.0 μm	E3 3.0-10 μm				
6DDUE-8-11	Pleated electrostatic (residential)	8	7 (0)	20.6	51.9	56.8	0	0.17 at 295 fpm	0.14 at 295 fpm	None
			11 ($3.2 * 10^7$)	17.4	69.9	88.8	0.3		0.14 at 295 fpm	
			11 ($6.9 * 10^7$)	15.6	69.2	87.3	0.7		0.14 at 295 fpm	
			11 ($1.0 * 10^8$)	20.9	75.4	92.4	1		0.21 at 295 fpm	
8NM-10-11	Pleated electrostatic (residential)	10	12 (0)	31.2	82.4	91.4	0	NA	0.43 at 295 fpm	None
			11 ($5.0 * 10^7$)	24.7	79.0	85.8	0.5		0.42 at 295 fpm	
			11 ($7.5 * 10^7$)	31.5	81.9	86.9	0.7		0.46 at 295 fpm	
			12 ($1.1 * 10^8$)	46.1	89.3	94.2	1.1		0.63 at 295 fpm	
C17FPP-8	Pleated electrostatic prefilter (commercial)	8	7 (0) – 12 x 24 x 2	39.1	75.5	64.7	0	0.30 at 500 fpm	0.55 at 492 fpm (0 weeks)	None
			8 (0)	48.3	91.1	81.3	0		0.44 at 492 fpm	
			13 ($3.2 * 10^7$)	51.7	94.6	98.2	0.3		0.47 at 492 fpm	
			13 ($6.6 * 10^7$)	51.7	94.6	98.0	0.7		0.47 at 492 fpm	
C15AAA-11	Pleated electrostatic prefilter (commercial)	11	8 (0) – 12" x 24" x 2"	47.5	72.9	71.4	0	0.38 at 500 fpm	0.40 at 492 fpm (0 weeks)	Collection efficiency was well below expected values.
			7 (0)	41.1	71.9	66.6	0		0.34 at 492 fpm	
			11 ($3.2 * 10^7$)	29.5	76.2	88.6	0.3		0.33 at 492 fpm	
			8 ($8.0 * 10^7$)	24.6	70.8	79.8	0.8		0.29 at 492 fpm	
			11 ($1.1 * 10^8$)	25.7	73.3	85.0	1.1		0.46 at 492 fpm	
C8GZ-13	Pleated synthetic box filter (commercial)	13	14 (0)	77.5	96.3	98.7	0	0.44 at 500 fpm	0.63 at 492 fpm	NA
			13 ($3.2 * 10^7$)	73.7	96.7	98.6	0.3		0.64 at 492 fpm	
			14 ($6.4 * 10^7$)	75.6	96.9	98.1	0.6		0.65 at 492 fpm	
			13 ($9.6 * 10^7$)	73.4	96.7	98.8	1		0.67 at 492 fpm	

[a]CT = concentration*time, in units of (particles*min)/cm^3.

Table 4-7. Summary of the Results from the Filter Conditioning Evaluations (Continued)

Filter	Description	MERV Rating (literature)	MERV Rating from testing (CT[a])	Average Collection Efficiencies (%)			Approximate Months of Use Simulated	Literature Pressure Drop (in. w.g.)	Measured Pressure Drop (in. w.g.)	Notes
				E1 0.3-1.0 µm	E2 1.0-3.0 µm	E3 3.0-10 µm				
5RM-11-1	Pleated electrostatic (residential)	11	7 (0)	19.2	64.9	68.7	0	0.12 at 250 fpm	0.25 at 295 fpm	NA
			11 ($3.4 * 10^7$)	15.8	68.8	86.8	0.3		NA	
			11 ($6.6 * 10^7$)	19.1	75.1	94.1	0.6		NA	
4FUA-12-3	Pleated electrostatic (residential)	12	12 (0)	39.7	80.8	92.1	0	NA	0.09 at 295 fpm	NA
			12 ($3.3 * 10^7$)	32.6	80.2	96.4	0.3		NA	
			11 ($6.8 * 10^7$)	31.0	78.7	96.6	0.7		NA	
			12 ($1.1 * 10^8$)	33.7	81.2	97.4	1.1		NA	
7AST-8-3	Pleated electrostatic (residential)	8	7 (0)	19.0	62.6	61.3	0	NA	0.09 at 295 fpm	NA
			11 ($3.2 * 10^7$)	17.2	72.0	86.6	0.3		NA	
			11 ($6.9 * 10^7$)	21.7	77.8	89.8	0.7		NA	
			12 ($1.0 * 10^8$)	32.7	87.6	96.7	1.0		NA	

[a]CT = concentration*time, in units of (particles*min)/cm^3.

Figure 4-51. Measured Collection Efficiency of Filter 6DDUE-8-11 During the Conditioning Evaluations

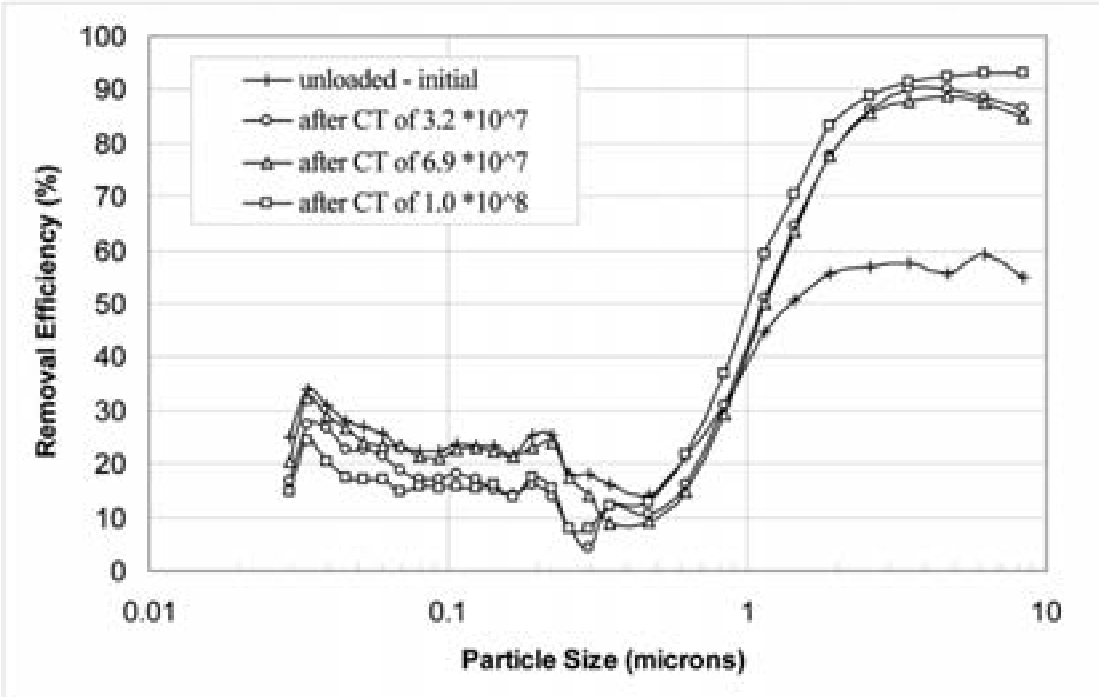


Figure 4-52. Measured Collection Efficiency of Residential Filter 6DDUE-8 During the Aging Evaluations

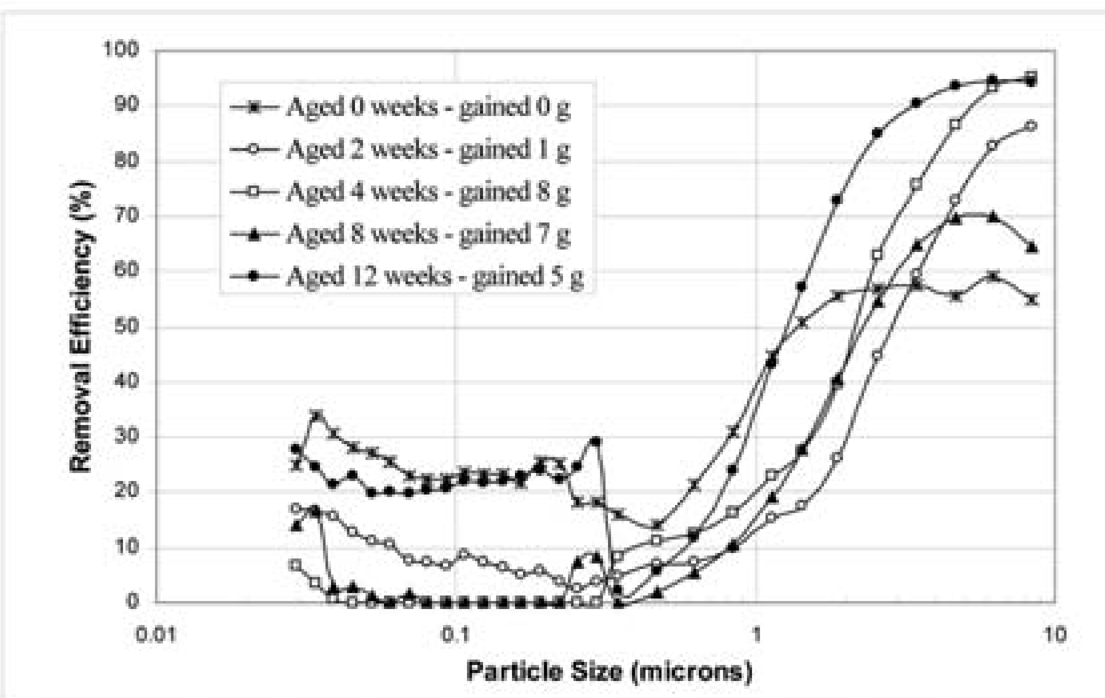


Figure 4-53. Measured Collection Efficiency of Filter 5RM-11-1 During the Conditioning Evaluations

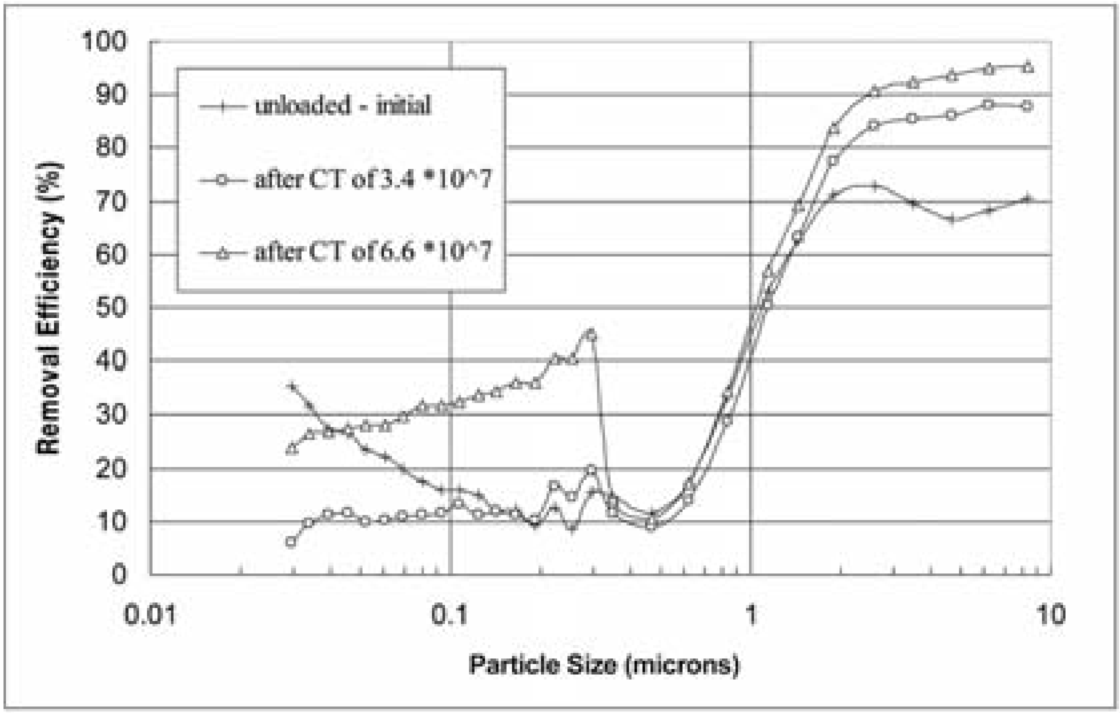


Figure 4-54. Measured Collection Efficiency of Filter 4FUA-12-3 During the Conditioning Evaluations

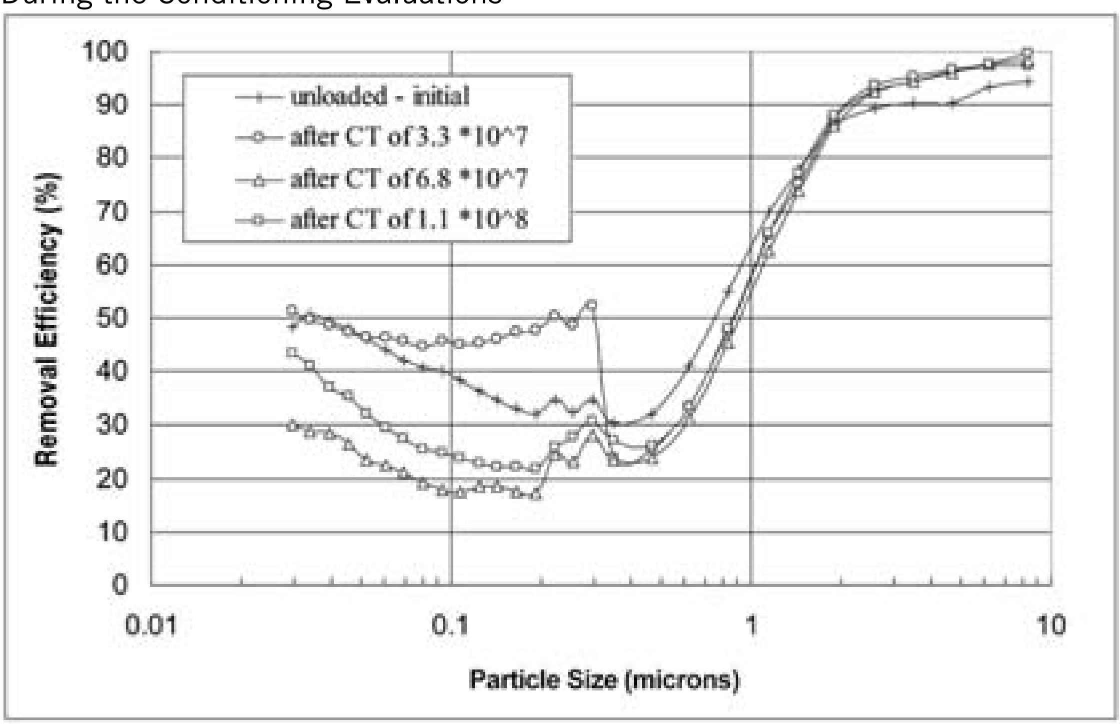


Figure 4-55. Measured Collection Efficiency of Filter 7AST-8-3 During the Conditioning Evaluations

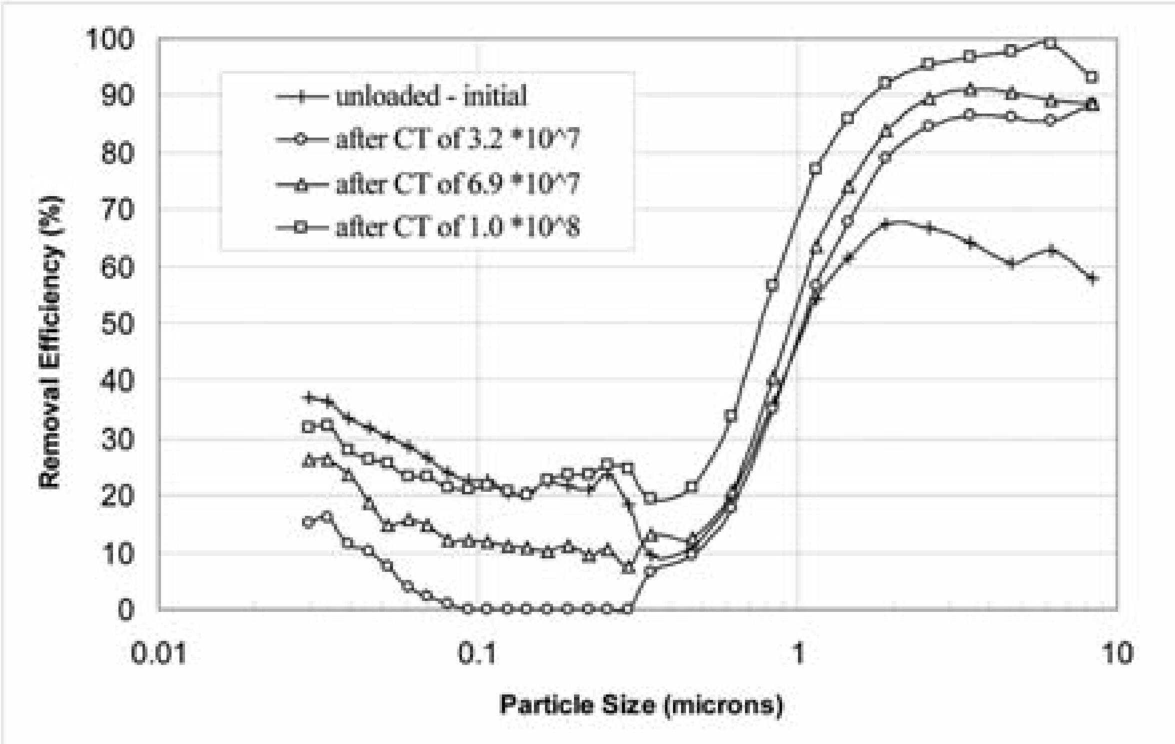


Figure 4-56. Measured Collection Efficiency of Filter 8NM-10-11 During the Conditioning Evaluations

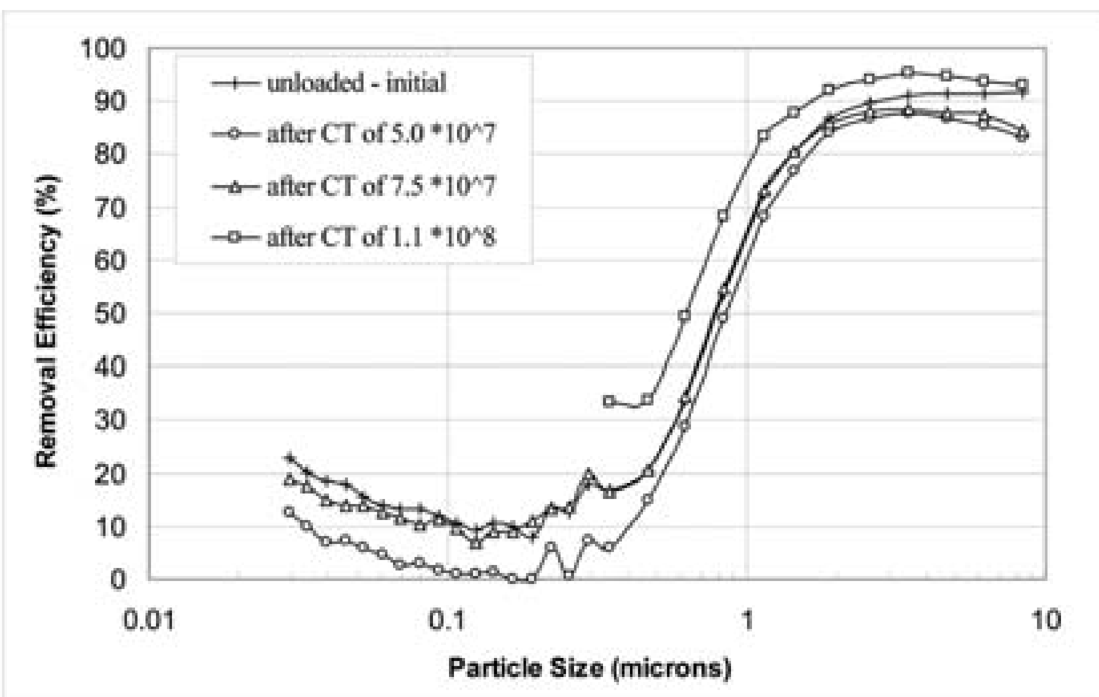


Figure 4-57. Measured Collection Efficiency of Residential Filter 8NM-10 During the Aging Evaluations

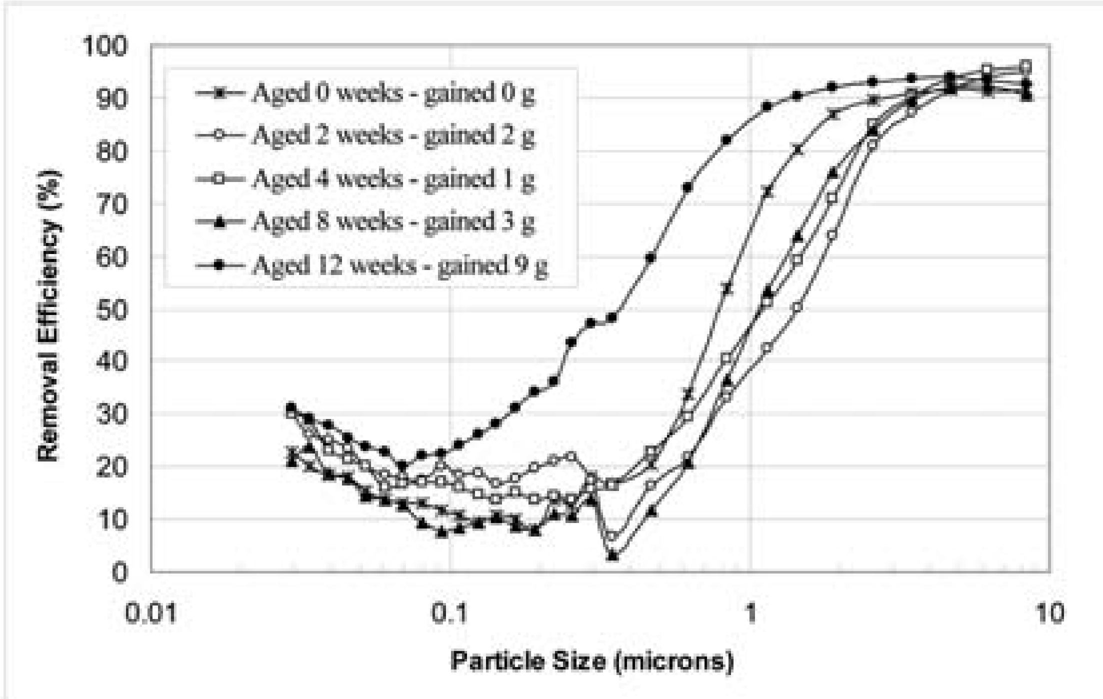


Figure 4-58. Measured Collection Efficiency of Filter C15AAA-11 During the Conditioning Evaluations

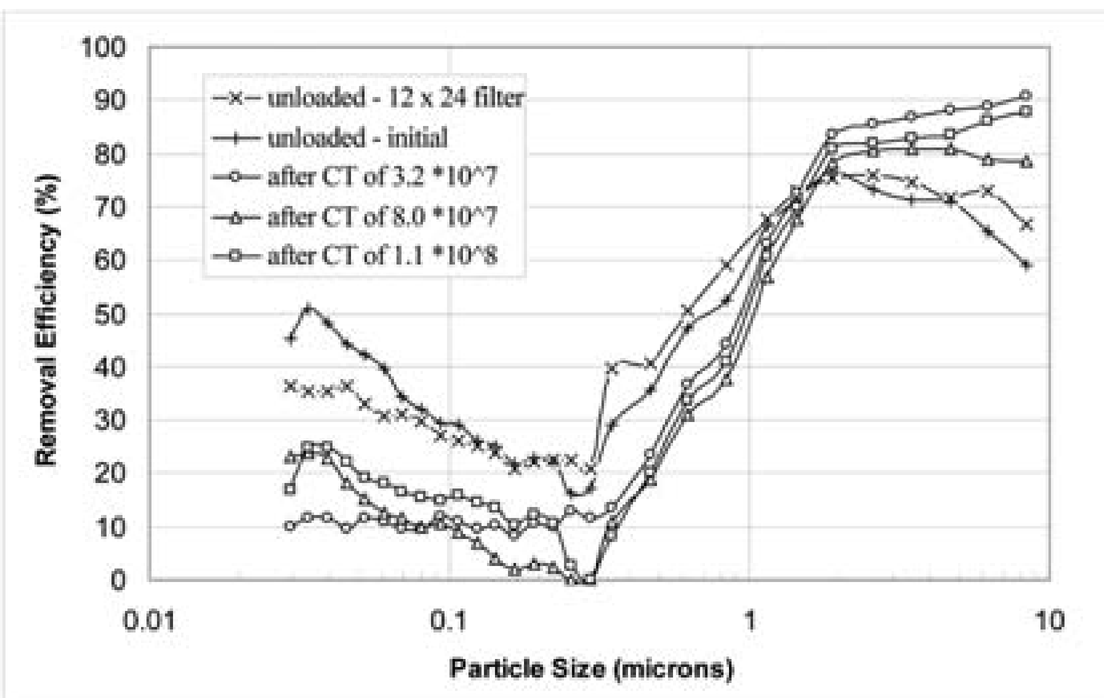


Figure 4-59. Measured Collection Efficiency of Commercial Filter C15AAA-11 During the Aging Evaluations

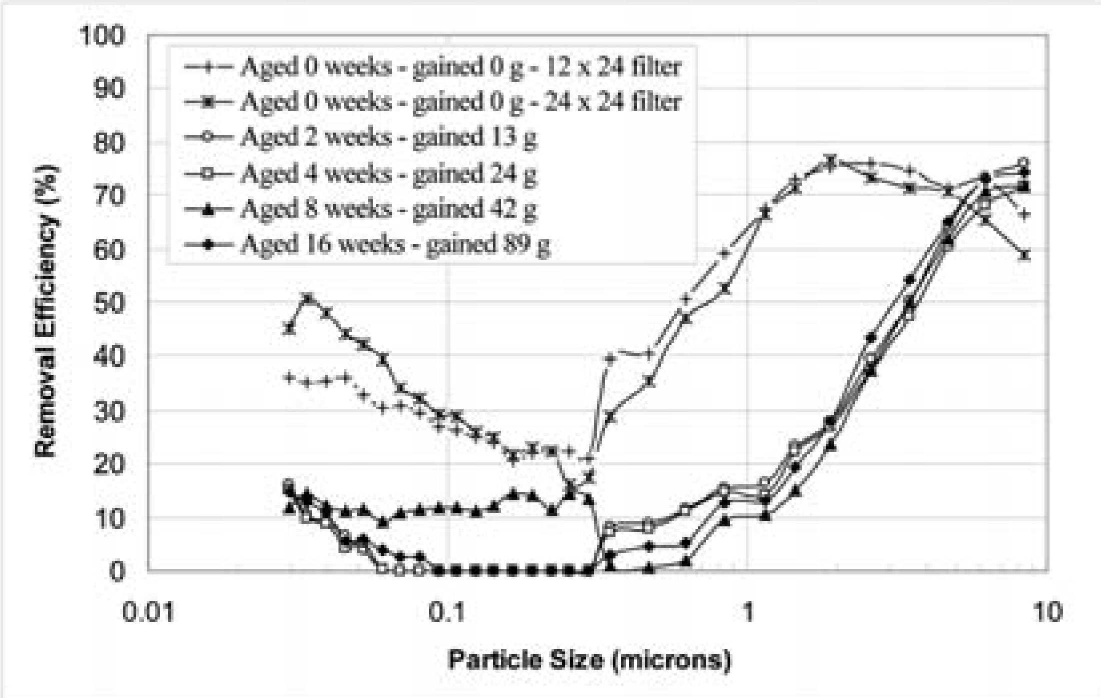


Figure 4-60. Measured Collection Efficiency of Filter C17FPP-8 During the Conditioning Evaluations

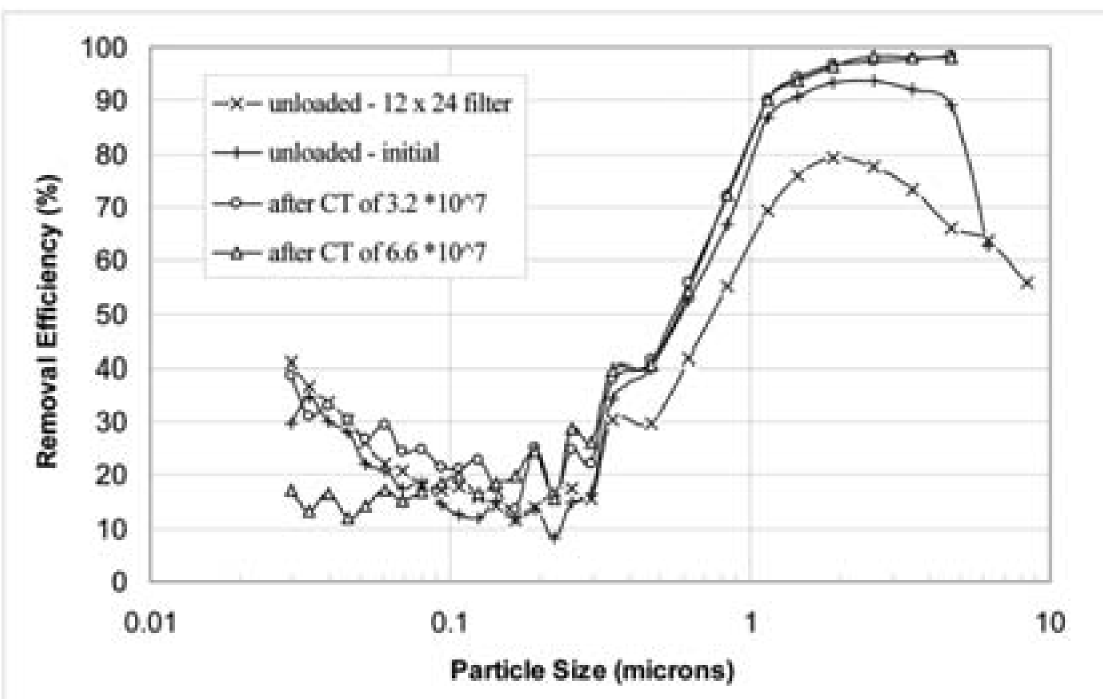


Figure 4-61. Measured Collection Efficiency of Commercial Filter C17FPP-8 During the Aging Evaluations

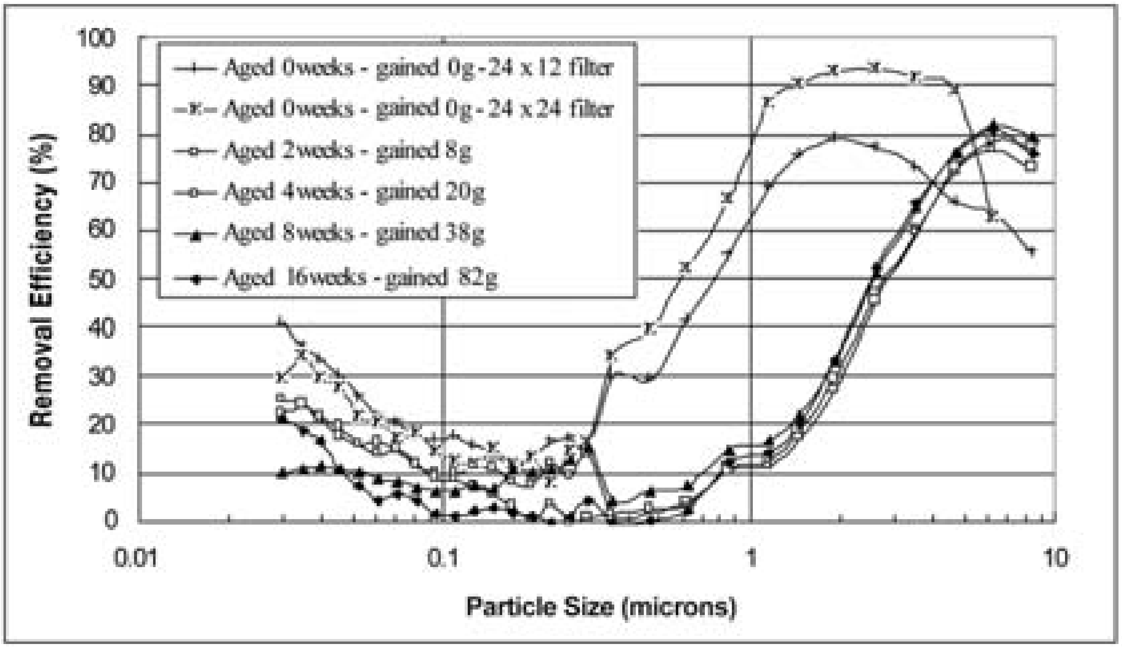


Figure 4-62. Measured Collection Efficiency of Filter C8GZ-13 During the Conditioning Evaluations

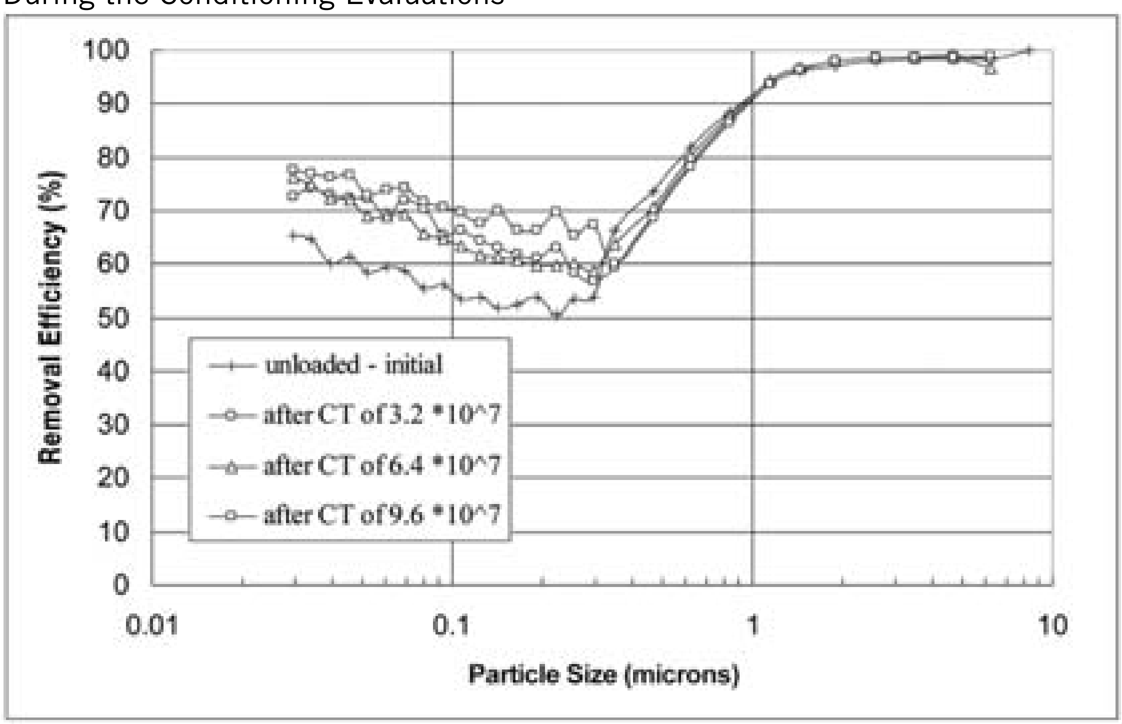
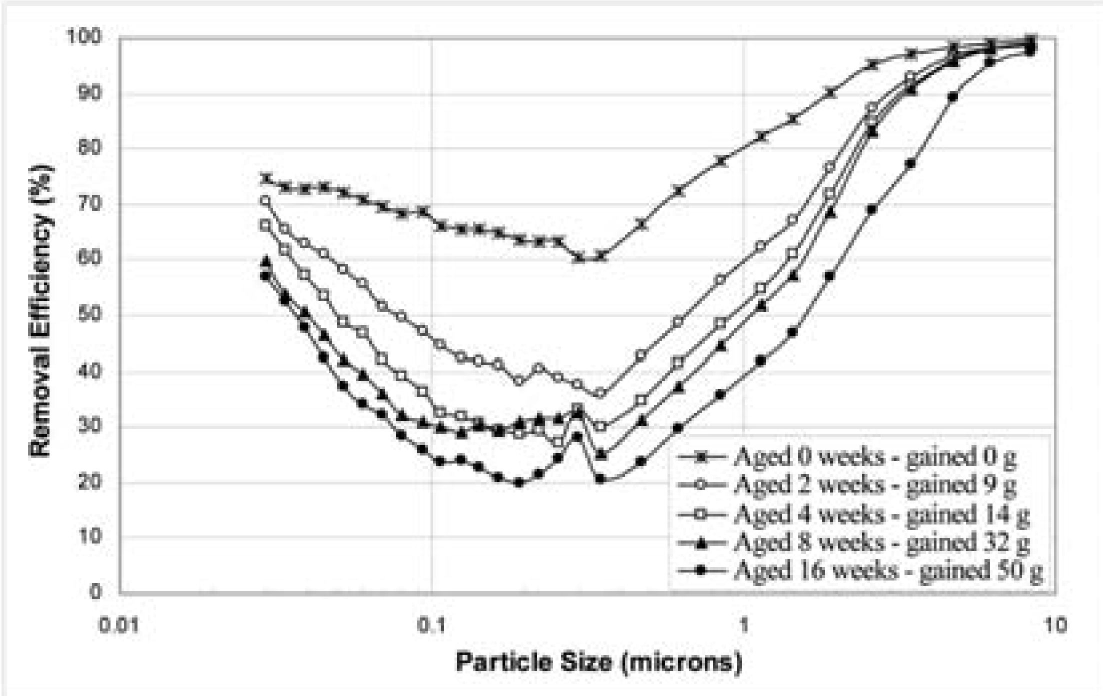


Figure 4-63. Measured Collection Efficiency of Commercial Filter C8GZ-13 During the Aging Evaluations



Similar to the residential filters, the aging and conditioning tests of commercial prefilter C15AAA-11 appeared to be consistent. As shown in Figure 4-58, the conditioning of commercial prefilter C15AAA-11 resulted in a noticeable decrease in collection efficiency for all particles less than approximately 1 µm, with no recovery during the approximately 1 month equivalent of conditioning. The aging of prefilter C15AAA-11 also resulted in a decrease (although more substantial) in collection efficiency for all particles smaller than approximately 4µm, with no recovery over 16 weeks of aging, as depicted in Figure 4-59.

In contrast, the aging and conditioning tests of the remaining two commercial filters (C17FPP-8 and C8GZ-13) did not produce consistent results. For commercial prefilter C17FPP-8, the collection efficiency increased slightly for all particles upon initial conditioning and remained at the same level with further conditioning (Figure 4-60). This result noticeably contrasted with the results from the aging evaluations (Figure 4-61), in which the collection efficiency decreased substantially for particles smaller than 4 µm with aging and did not increase over 16 weeks of use. For commercial box filter C8GZ-13, the results from the aging and conditioning evaluations contrasted even more strongly. In the conditioning evaluation shown in Figure 4-62, the collection efficiency of filter C8GZ-13 remained essentially constant during the approximately 1 month equivalent of conditioning, even increasing slightly for particles smaller than 0.3 µm. However, during the 16 weeks of aging, filter C8GZ-13 consistently and continually decreased in collection efficiency for all particles during the entire period, as shown in Figure 4-63.

It is not known why the trends in the results from the conditioning evaluations are consistent with the aging results for three of the filters but inconsistent with the aging results for the other two filters. Further investigation of these contrasting results seems warranted but is beyond the scope of the present effort. It should again be noted that during the conditioning evaluations, a single filter was used. In contrast, the aging evaluations were performed with five different filters of identical make, model, and size. Therefore, some variability is present in the aging evaluations due to the different performance levels of the individual filters, as well as between the filters used in the conditioning evaluation and the aging evaluations.

4.4.2 Results from the Conditioning Evaluations – Electronic Air Cleaners

As described in Section 3.5, three EACs were evaluated by the inert aerosol methods described in Section 3.1 both before and after exposure to silicon vapor. The purpose of the exposure to silicon vapor was to compare the results from exposure to silicon vapor to the results from the "in-use" tests to determine whether the silicon vapor exposure resulted in a realistic assessment of their likely performance after one month of actual use.

A summary of the results is provided in Table 4-8. Individual results, along with a comparison to the results from the aging tests of the EACs are provided in Figures 4-64, 4-65, and 4-66. As shown in Figures 4-64 and 4-66, the silicon vapor exposure of Units A and P appeared to cause a very similar degradation to that likely to be observed after 1 month of ambient aging (672 hours of use). In both Figures 4-64 and 4-66, the collection efficiency of the electronic air cleaner degraded more than that observed during 336 hours (2 weeks) of ambient use but less than that observed after 1,008 hours (6 weeks) of ambient use. For Unit H, however, the silicon vapor exposure degraded the unit's performance well beyond that observed after even 2,016 hours of ambient aging (12 weeks of continuous operation).

It is not known why the results from the aging and conditioning evaluations are consistent for units A and P but inconsistent for Unit H. It could be a result of a large number of design and component differences between the three units. Given the approximately 50% decrease in pressure drop in Unit H after silicon vapor exposure, and the alteration in the shape of the collection efficiency curve, it is possible that the exposure allowed leakage to occur within the unit. Further investigation of the contrasting results for Unit H seems warranted but is beyond the scope of the present effort.

It should be noted that in contrast to the filter evaluations, during the EAC aging evaluations, a single unit was used. Therefore, no variability was present within the EAC aging evaluations due to the different performance levels of individual units. In addition, the initial collection efficiency tests (shown in Table 4-3 and Figure 4-19) indicated that the variability between the EACs used in the conditioning evaluation versus those used in the aging evaluations was very small.

Table 4-8. Summary of the Results from the Silicon Vapor Exposures of the Electronic Air Cleaners

Unit	MERV Rating from Vendor	MERV Rating from Testing (Exposure Status)	Average Collection Efficiencies (%)			Literature Pressure Drop (in. w.g.)	Measured Pressure Drop (in. w.g.)	Notes
			E1 0.3–1.0 μm	E2 1.0–3.0 μm	E3 3.0–10 μm			
A	15	15 (before)	90.8	94.4	96.6	0.17 AT 504 fpm	0.11 at 295 fpm	Very consistent with aging tests
		15 (after)	86.6	93.9	98.1		0.13 at 295 fpm	
H	Up to 12	15 (before)	91.5	97.2	98.8	0.06 at 295 fpm	0.11 at 295 fpm	Not consistent with aging tests
		6 (after)	52.3	53.8	47.1		0.05 at 295 fpm	
P	NA	14 (before)	82.5	95.3	96.9	0.11 at 504 fpm	0.08 at 295 fpm	Very consistent with aging tests
		7 (after)	33.3	43.6	50.5		0.06 at 295 fpm	

Figure 4-64. Measured Collection Efficiencies for Electronic Air Cleaner A Before and After Exposure to Silicon Vapor

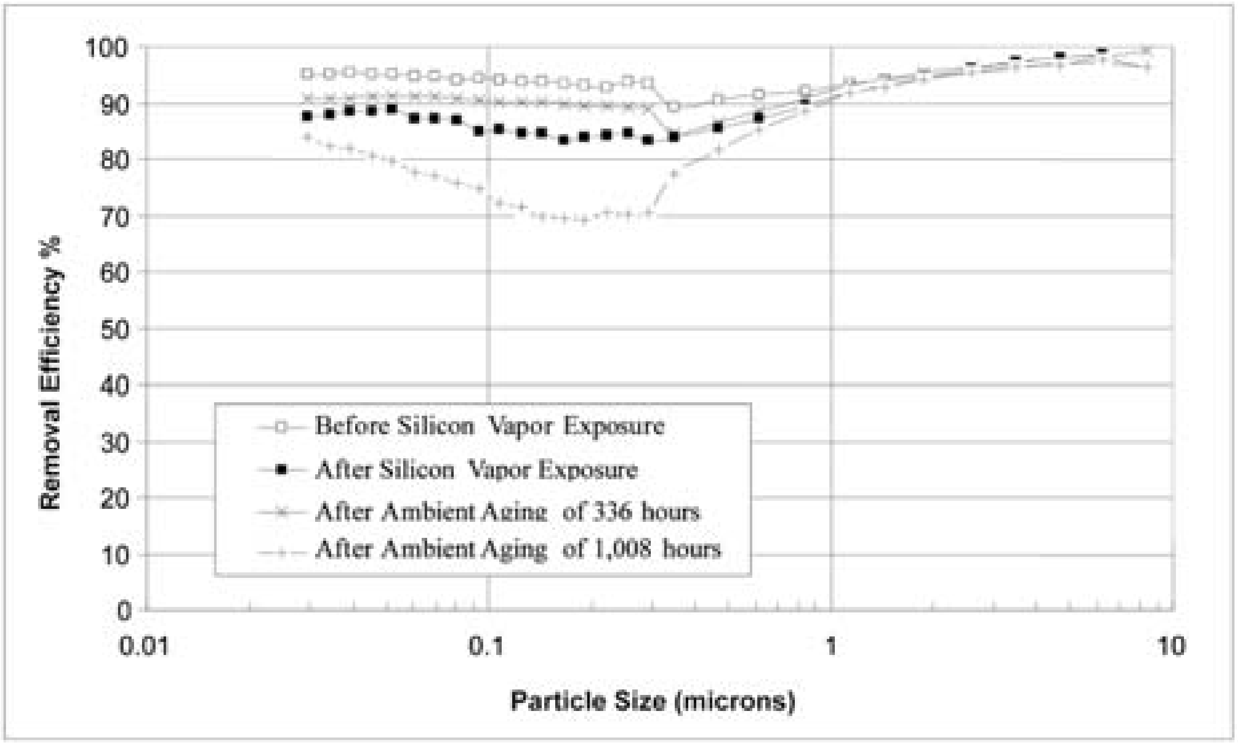


Figure 4-65. Measured Collection Efficiencies for Electronic Air Cleaner H Before and After Exposure to Silicon Vapor

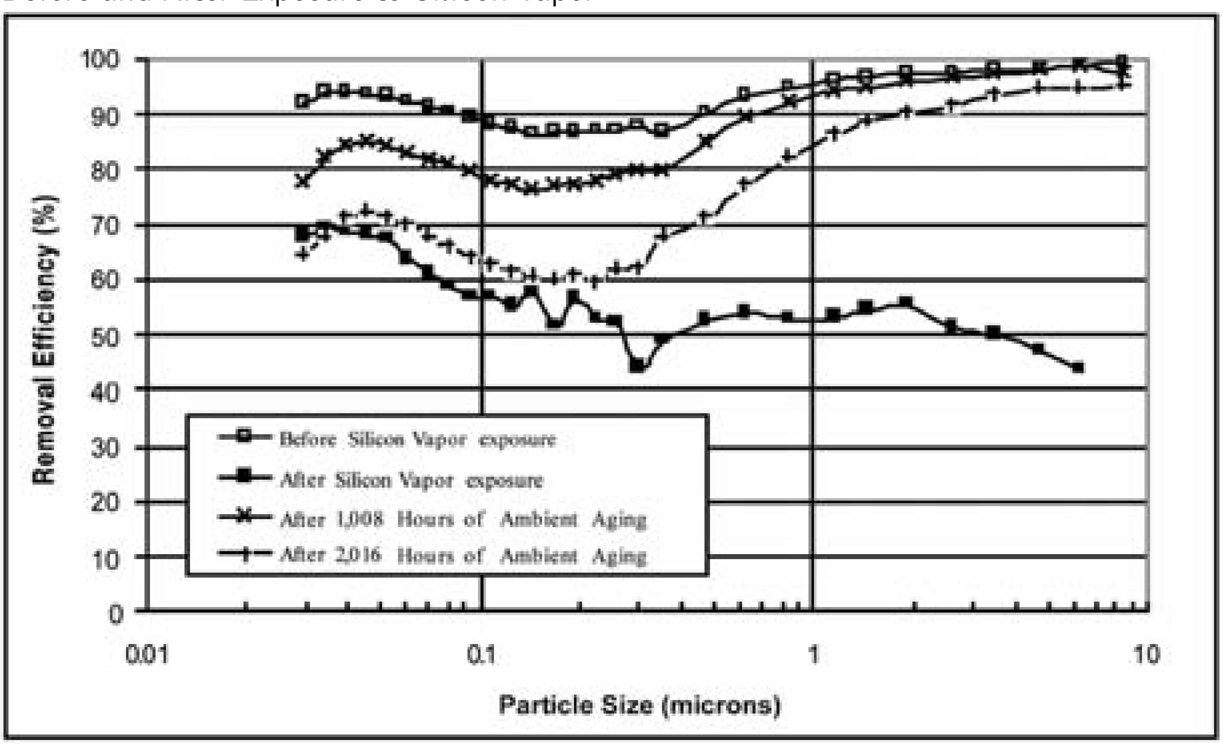
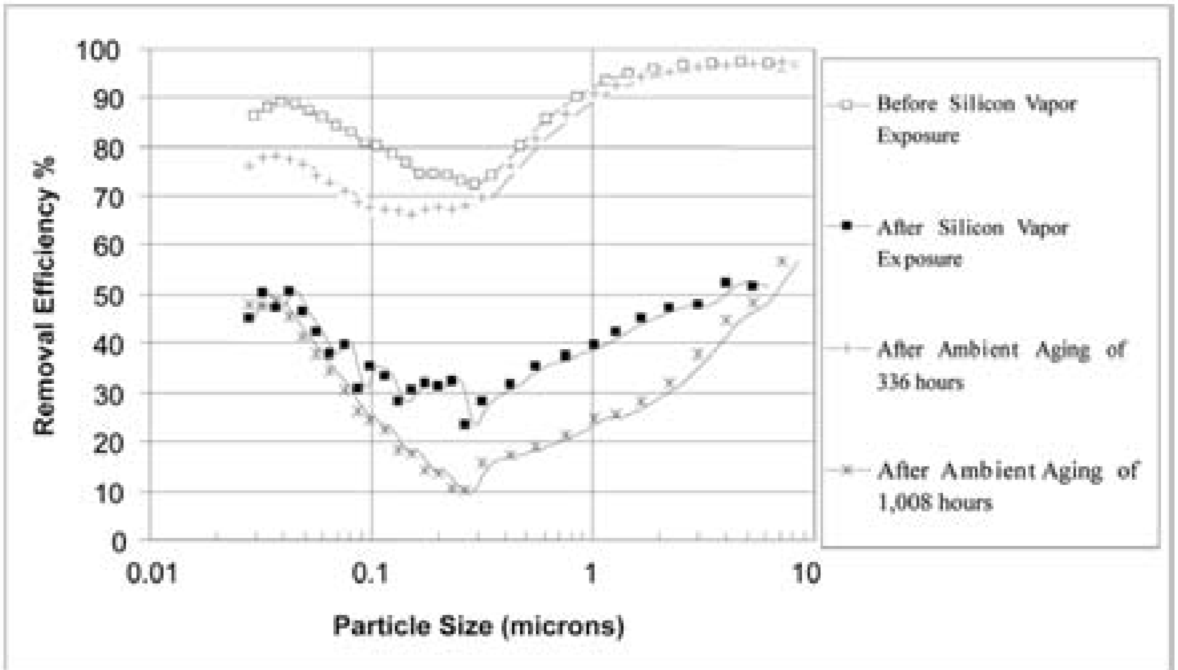


Figure 4-66. Measured Collection Efficiencies for Electronic Air Cleaner P Before and After Exposure to Silicon Vapor



4.5 Quality Assurance

Work under this task was completed in accordance with a pair of EPA-approved quality assurance test plans (QAPP) entitled "Research on Air Cleaning and HVAC Systems for Protecting Buildings from Terrorist Attacks; Test/Quality Assurance Plan for Task 2: Development of Performance Information for Common Ventilation Filters" (Battelle, 2005a), and "Research on Air Cleaning and HVAC Systems for Protecting Buildings from Terrorist Attacks; Test/Quality Assurance Plan for Task 3: Development of Performance Information for Electronic Air Cleaners" (Battelle, 2005b). The text from these two QAPPs was included in the relevant portions of this report, for example, the development of the filter and electronic air cleaner tests matrices (Section 2), the inert aerosol and bioaerosol test procedures (Sections 3.1.1 and 3.2.1), and the data analysis procedures (Sections 3.1.2 and 3.2.2).

In accordance with the QAPPs (Battelle 2005a; Battelle, 2005b), an external quality assurance (QA) audit of Tasks 2/3 was performed by an EPA staff member and a designated representative on 9 August 2006 at Battelle's Columbus facility. The quality assurance inspectors reviewed the sample handling logs, standard operating procedures, test record sheets, instrument calibration sheets, data logs and data sheets from the inert and bioaerosol tests, and various other documentation. In addition, the quality assurance inspectors witnessed the performance of a bioaerosol test. Official documentation from the QA inspectors was received on 8 September 2006. No corrective actions were deemed necessary. Additional information on the quality assurance procedures and results can be found in Appendix I.

5.0 Curve Fitting to the "Off-The-Shelf" Air Cleaner Results

As clearly evidenced by this study, a variety of options exist for the removal of particles in residential and commercial HVAC systems. There are a number of selection criteria to be considered when choosing an air cleaner for a specific HVAC system, including (but not limited to) cost, pressure drop, service life, maintenance requirements, collection efficiency, power requirements, and required/desired clean air specifications. In order to choose the optimal air cleaner for a specific HVAC system, all of these factors need to be considered and, in some cases, modeled. Therefore, empirical equations were developed based on the data acquired during this effort relating particle collection efficiency to particle physical diameter over the range of 0.03 to 10 µm. These equations can be incorporated into indoor air quality models. The results from these modeling efforts are provided below.

5.1 Curve Fits to the Inert Aerosol Filter Evaluations

Empirical equations were developed based on the data acquired during the evaluations of the "off-the-shelf" filters relating particle collection efficiency to particle physical diameter over the range of 0.03 to 10 µm. These equations were developed only for unaged, unconditioned filters, and one curve was fit to all of the filters whose test results resulted in a given MERV rating. The curves were fit using TableCurve 2D software (SYSTAT Software Inc.). To generate the curves, all of the experimental collection efficiency results for a given MERV rating were combined into one spreadsheet. When more than one set of data was used, the data were combined by averaging the penetrations and weighting the mean values proportionally to the inverse of the standard deviation of the values. At the direction of the sponsor, a 3rd order polynomial was fit between the log of the penetration and the log of the particle diameter. To avoid difficulties with taking logarithmic values of penetrations of 0%, the curves for the MERV 16 and HEPA filters had to be fit to the natural logarithm and the numerical penetration, respectively, versus the log of the particle diameter. The results from the curve fits are summarized in Table 5-1 and illustrated in Figures 5-1 through 5-9. As shown in Table 5-1 and the various figures, all but one of the curve fits possessed correlation coefficients (r squared) greater than 0.89, indicating an excellent representation of the data. The MERV 6 curve fit possessed a lower correlation value (0.83), but as shown in Figure 5-2, the fitted curve matched the data well. In all cases, it is not recommended that the curve fits be extrapolated outside of the particle size range used to develop the curve fits (0.03 to 10 µm). It should be noted that the curve fits will provide an empirically validated prediction for the performance of a filter that performs at a given MERV rating, not a prediction for a particular make and model of filter.

Table 5-1. Summary of the Results from the Curve Fits to the Inert Aerosol Evaluations of Unaged Unconditioned Air Filters

MERV Rating	Equation	Parameters	Correlation Coefficient (r^2)
5	$Y = a + bx + cx^2 + dx^3$ where Y = log of percent penetration x = log of particle diameter	a = 1.8906 b = –0.1722 c = 0.0307 d = 0.0793	0.8935
6	$Y = a + bx + cx^2 + dx^3$ where Y = log of percent penetration x = log of particle diameter	a = 1.9311 b = –0.1441 c = –0.1243 d = –0.0234	0.8332
7	$Y = a + bx + cx^2 + dx^3$ where Y = log of percent penetration x = log of particle diameter	a = 1.7467 b = –0.3314 c = –0.0036 d = 0.1381	0.9064
8	$(1/Y) = a + bx + cx^2 + dx^3$ where Y = log of percent penetration x = log of particle diameter	a = 0.5839 b = 0.1675 c = 0.1289 d = 0.0188	0.9658
10	$Y = a + bx + cx^2 + dx^3$ where Y = log of percent penetration x = log of particle diameter	a = 1.7083 b = –0.5759 c = –0.6721 d = –0.1775	0.9852
12	$Y = a + bx + cx^2 + dx^3$ where Y = log of percent penetration x = log of particle diameter	a = 1.3943 b = –0.9080 c = –0.6240 d = –0.0404	0.9902
14	$Y = a + bx + cx^2 + dx^3$ where Y = log of percent penetration x = log of particle diameter	a = 0.9531 b = – 1.4941 c = –0.8443 d = –0.0013	0.9668
16	$\ln Y = a + bx + cx^2 + dx^3$ where Y = percent penetration x = log of particle diameter	a = 0.3855 b = –2.0698 c = 0.5326 d = 1.3895	0.9728
16+ (HEPA)	$Y = a + bx + cx^2 + dx^3 + ex^4$ where Y = percent penetration x = log of particle diameter	a = 0.0361 b = –0.3506 c = 0.5119 d = 0.0481 e = –0.1816	0.8917

Figure 5-1. Curve Fit to the Empirical Data for the Single Unaged, Unconditioned MERV 5 Filter

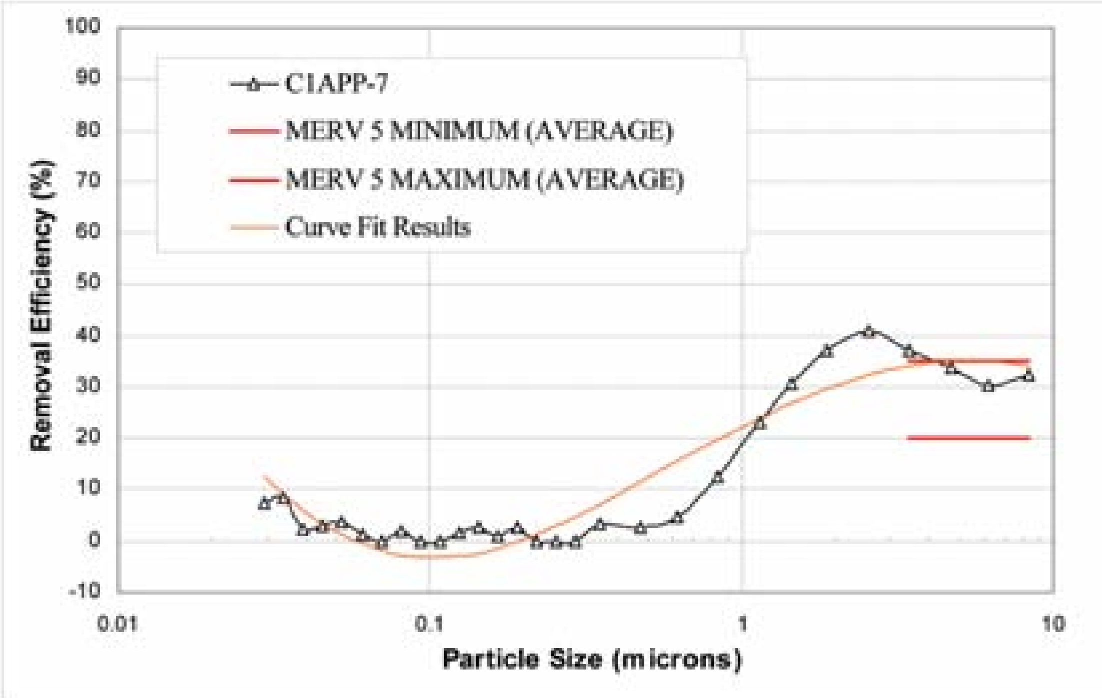


Figure 5-2. Curve Fit to the Empirical Data for the Two Unaged, Unconditioned MERV 6 Filters

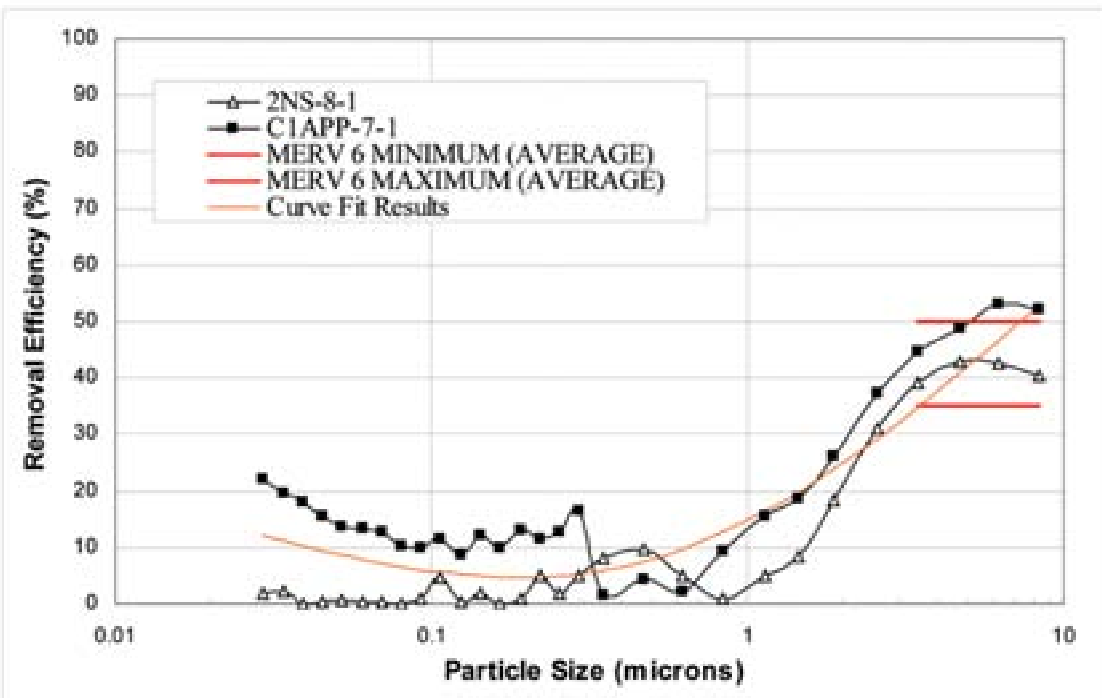


Figure 5-3. Curve Fit to the Empirical Data for the Six Unaged, Unconditioned MERV 7 Filters

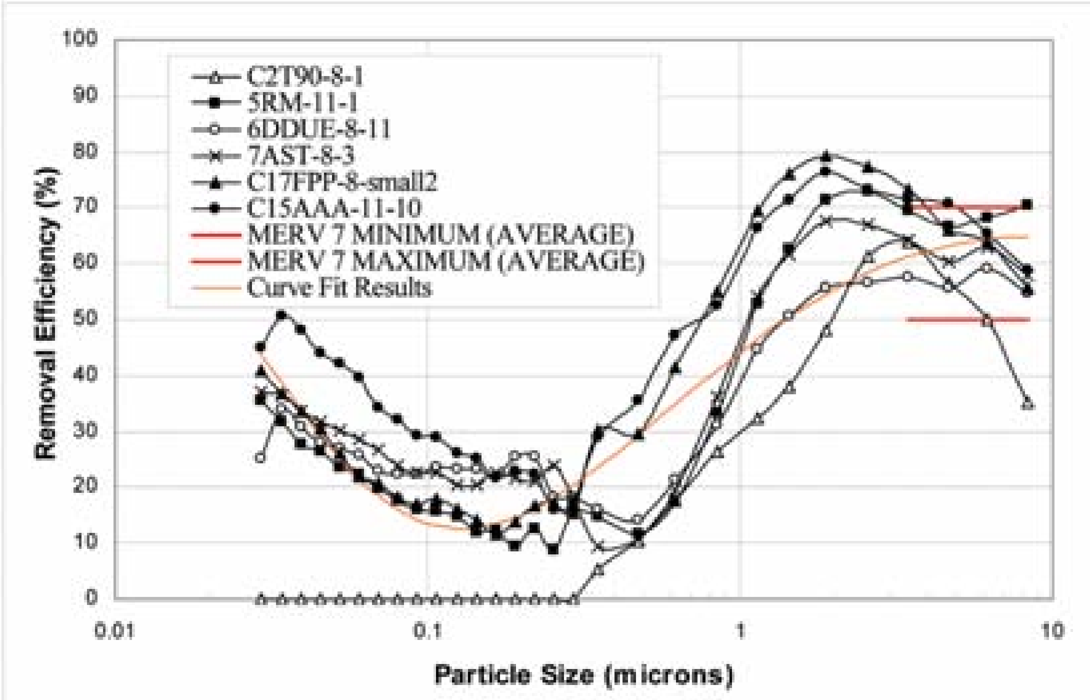


Figure 5-4. Curve Fit to the Empirical Data for the Four Unaged, Unconditioned MERV 8 Filters

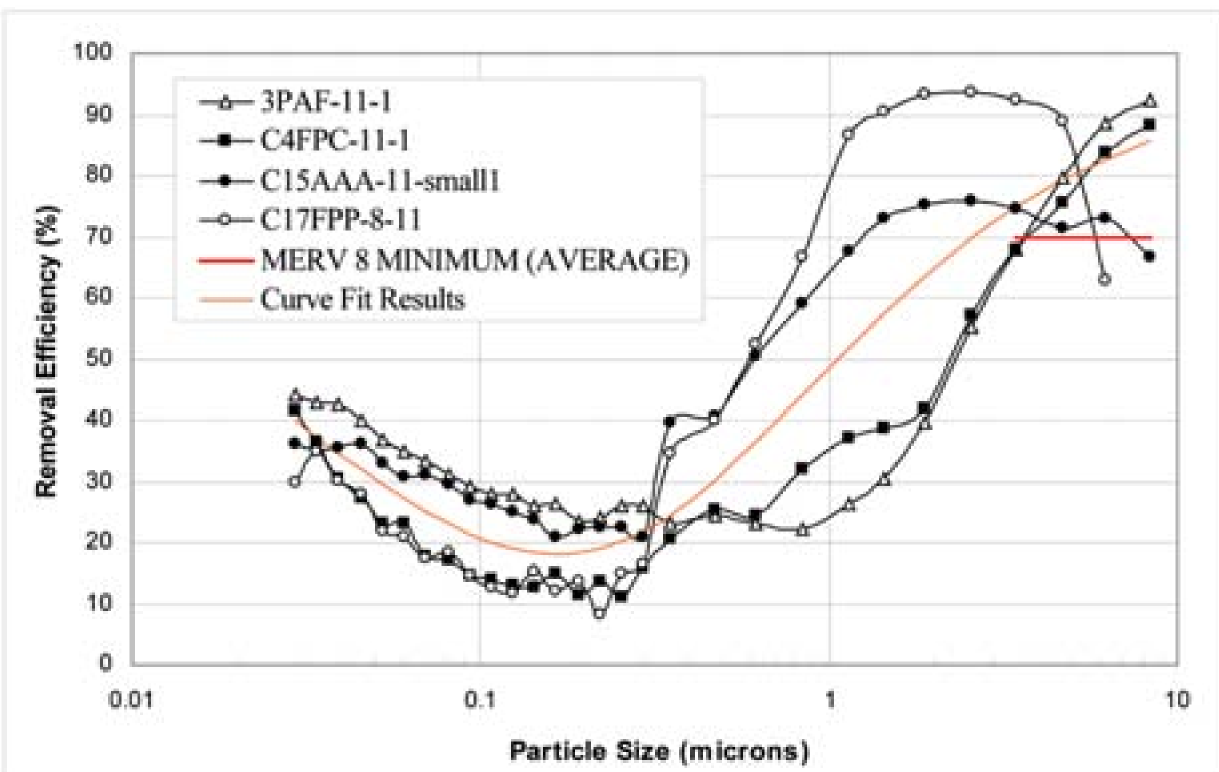


Figure 5-5. Curve Fit to the Empirical Data for the Single Unaged, Unconditioned MERV 10 Filter

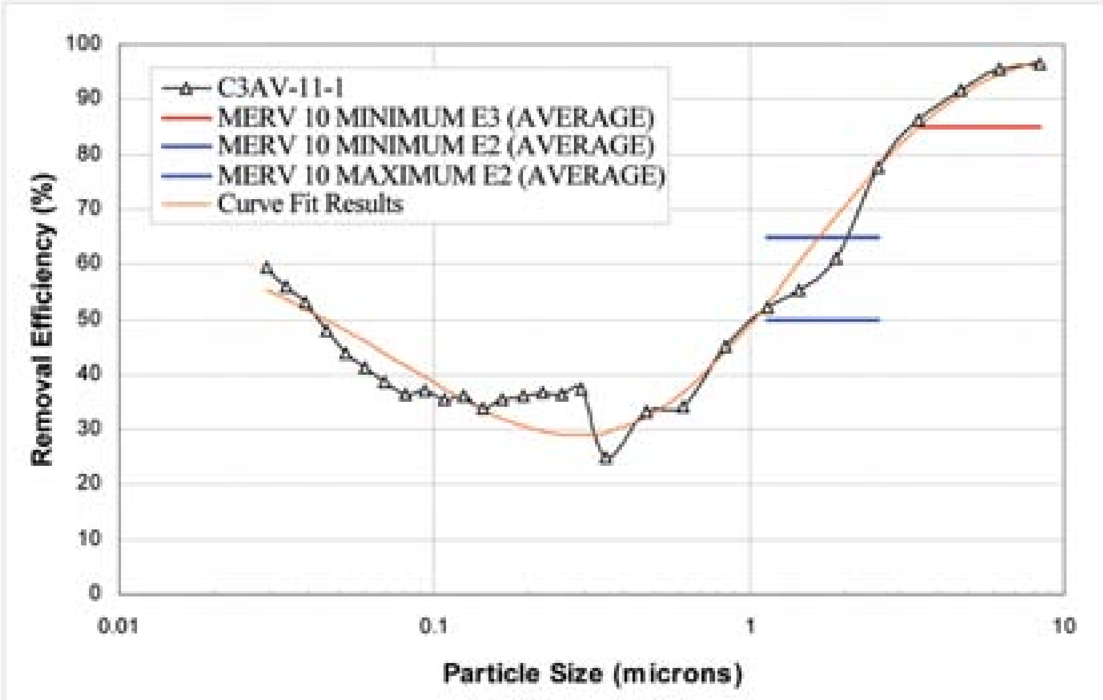


Figure 5-6. Curve Fit to the Empirical Data for the Five Unaged, Unconditioned MERV 12 Filters

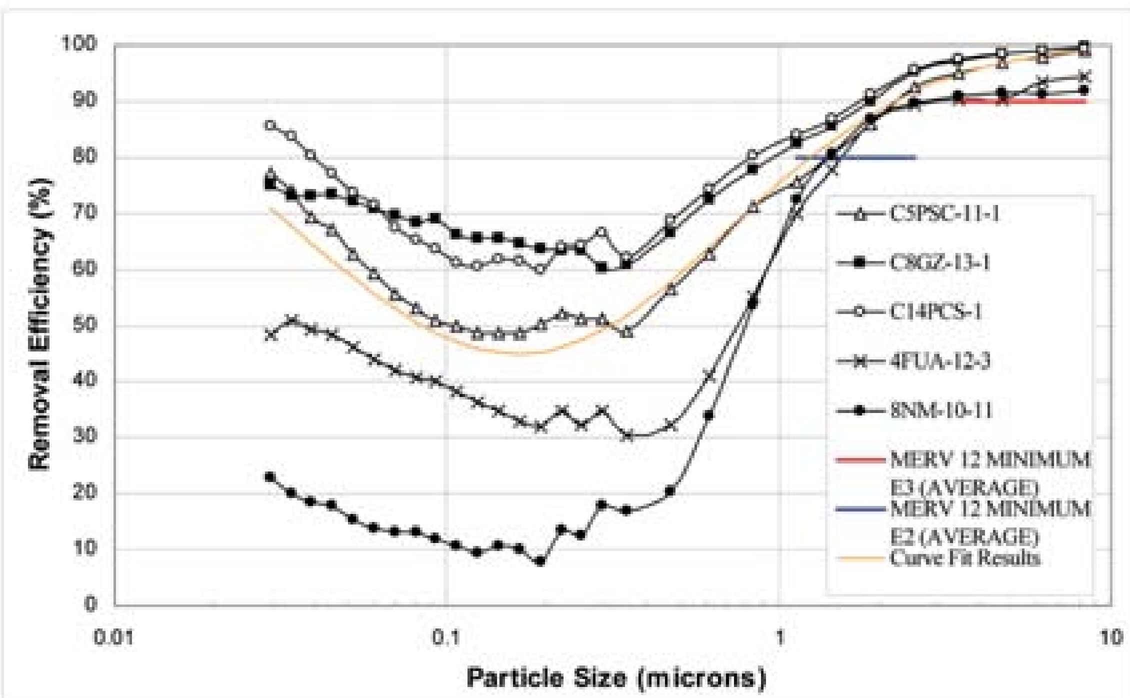


Figure 5-7. Curve Fit to the Empirical Data for the Four Unaged, Unconditioned MERV 14 Filters

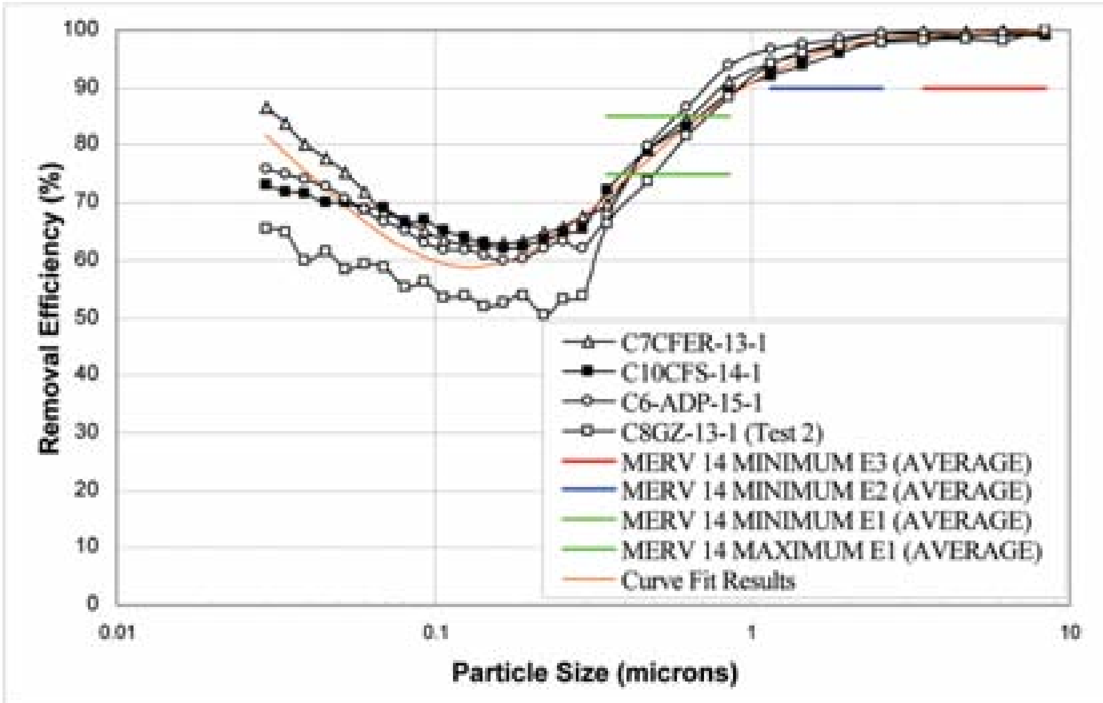


Figure 5-8. Curve Fit to the Empirical Data for the Three Unaged, Unconditioned MERV 16 Filters

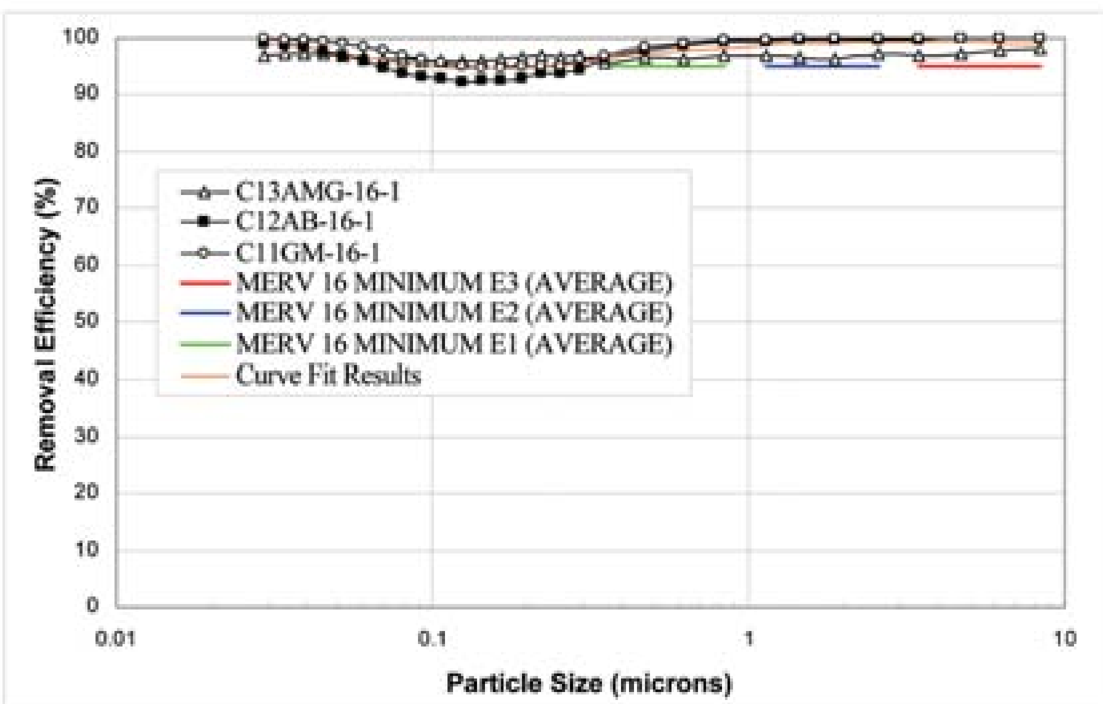
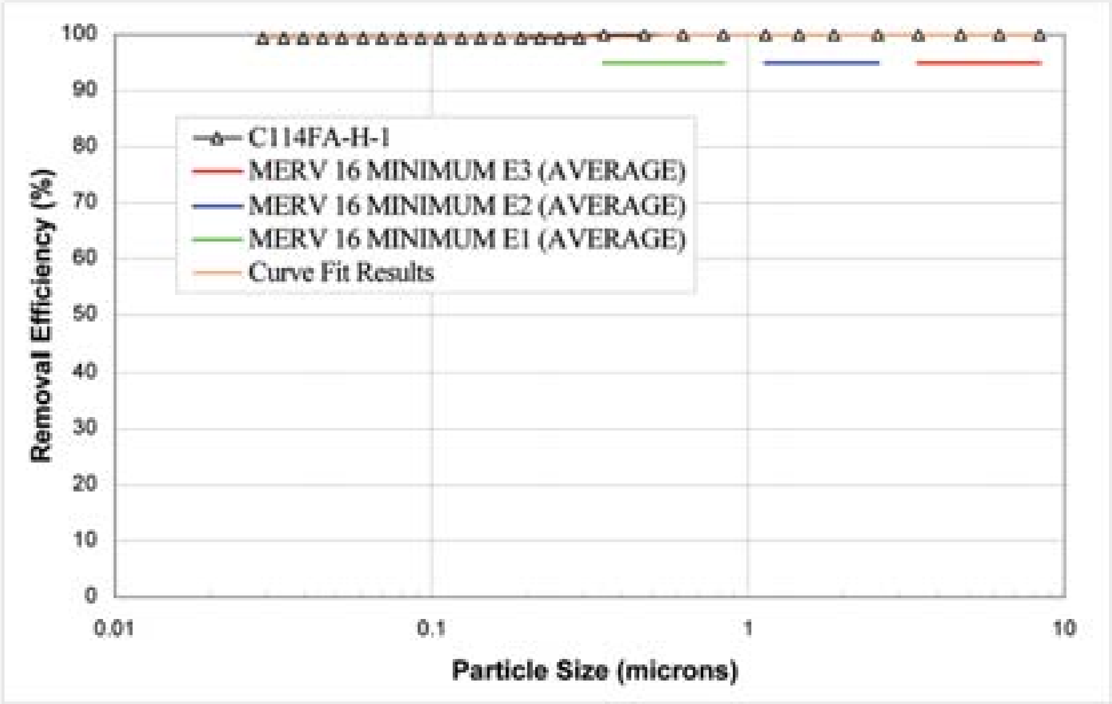


Figure 5-9. Curve Fit to the Empirical Data for the Single Unaged, Unconditioned MERV 16+ (HEPA) Filter



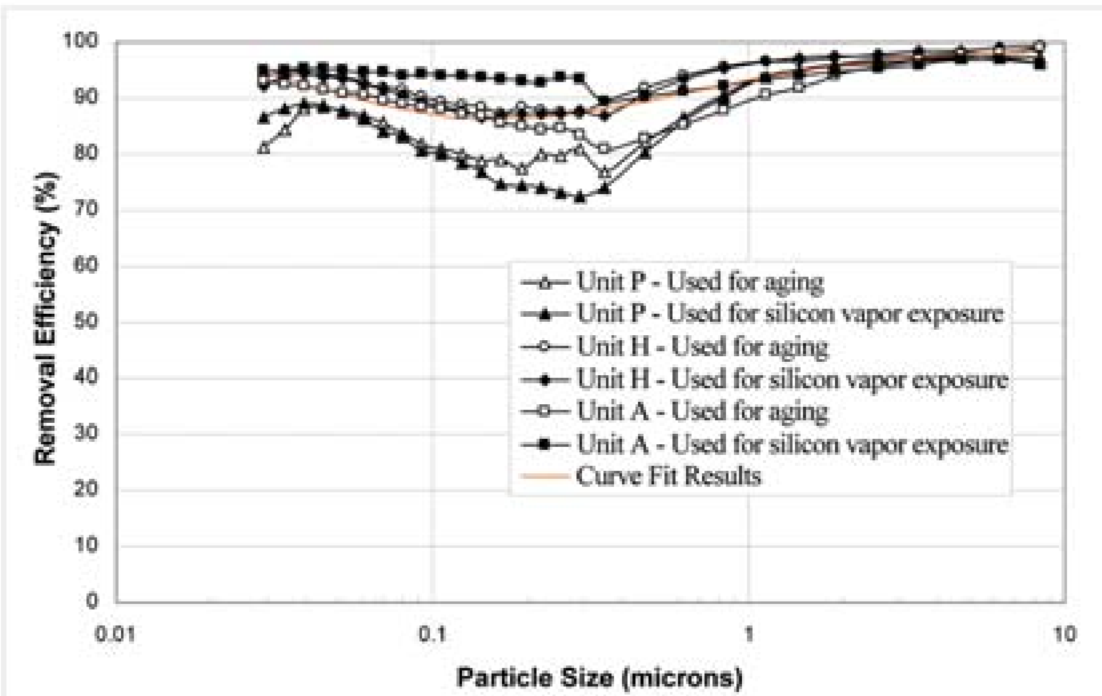
5.2 Curve Fits to the Inert Aerosol Electronic Air Cleaner Evaluations

In contrast to the curve fitting of the filter results, a single curve was fit to all of the "off-the-shelf" electronic air cleaner results. The results are illustrated in Table 5-2 and Figure 5-10. As shown in Table 5-2 and Figure 5-10, an excellent correlation between the collected data and the curve fit was obtained, as the EACs all had very similar MERV ratings (either 14 or 15) and similar collection efficiency curves.

Table 5-2. Summary of the Results from the Curve Fits to the Inert Aerosol Evaluations of Unaged Unconditioned Electronic Air Cleaners

MERV Rating	Equation	Parameters	Correlation Coefficient (r^2)
14 and 15 (all unaged unconditioned EACs)	$Y = a + bx + cx^2 + dx^3$ where Y = log of percent penetration x = log of particle diameter	a = 0.8422 b = –0.6469 c = –0.2157 d = 0.1645	0.9600

Figure 5-10. Curve Fit to the Empirical Data for the Six Unaged, Unconditioned Electronic Air Cleaners



6.0 Conclusions and Recommendations

As described in the initial sections of this report, four distinct types of testing were performed under this effort. First, a total of 27 commonly used air cleaning devices (24 filters and 3 EACs) were acquired and evaluated for their pressure drop and collection efficiency, as received ("off-the-shelf"). Empirical equations were developed for the data collected during these tests relating particle collection efficiency to particle physical diameter over the range of 0.03 to 10 µm. Second, ten devices (seven filters and three EACs) were evaluated for their bioaerosol collection efficiency. Third, a different subset of ten devices (seven filters and three EACs) were evaluated for their pressure drop and collection efficiency after approximately 1 or 2 weeks, 2 or 4 weeks, 6 or 8 weeks, and 12 or 16 weeks of normal use. Fourth, eight filters and three EACs were "conditioned" via methodologies anticipated to simulate an actual use environment. Eight electrostatic filters were conditioned by loading with a submicrometer inert aerosol, while the three EACs were evaluated both before and after exposure to silicon vapor. Summaries of the results and conclusions from each of these efforts are provided below.

6.1 Results from Inert Aerosol Evaluations of "Off-the-Shelf" Filters

The measured pressure drops of the "off-the-shelf" filters generally corresponded quite well (± 30%) with the information provided by the vendors, although, in a few cases, the measured pressure drops were somewhat greater. With the exception of several MERV 11 filters, the MERV ratings that were determined from the tests were generally equivalent or within one or two MERV ratings of the manufacturer data. The testing during this study consisted of evaluating of single filters; therefore, the results may not be representative of typical performance.

Except for the MERV 8 filters, the collection efficiency curves obtained for the filters with identical MERV ratings were similar in shape. Two of the MERV 8 filters possessed curves with shapes similar to those of lower MERV ratings (MERV 5 through 7), and two of the MERV 8 filters possessed curves similar to those with greater MERV ratings (MERV 9 through 16). For all of the MERV ratings, collection efficiencies measured with the Climet model 500 Spectrometer (OPC) (0.3 to 10 µm) generally corresponded very well to the collection efficiencies measured with the TSI SMPS (0.03 to 0.3 µm). The most penetrating particle size was consistently in the 0.1 to 0.3 µm range, which is consistent with typical filtration efficiency curves.

Table 6-1 provides a summary of the results from the inert aerosol evaluations of unconditioned, unaged ("off-the-shelf") filters. As shown in Table 6-1, the pressure drops of the filters between MERV 5 and 10 at 370 fpm did not appear to be substantially different, with a good deal of overlap between the average pressure drops. However, there was a significant increase in pressure drops between the MERV 10 and MERV 12 filters, between the MERV 14 and MERV 16 filters, and between the MERV 16 filters and the HEPA filter. As expected, the collection efficiency of the filters generally increased with MERV rating. Therefore, consumers of air filters will need to balance the higher pressure drops and costs of MERV 12 to MERV 16 filters with the expected increase in performance. (MERV 12 was the highest MERV rating found for a residential filter.)

In contrast to procurement of the residential filters, during procurement of the commercial filters, difficulties in obtaining serviceable filters of the correct model and size were experienced with nearly one-third of the procured test filters. These difficulties included shipment of incorrect (but similar) models, incorrect sizes, incorrect frame types and materials, and damaged or improperly constructed filters. For consumers concerned with filter performance, care must be taken to inspect filters before use to ensure that the filters are appropriate for use.

As described in Section 5 and Table 5-1, curves were fit to the collection efficiencies that were measured for the "off-the-shelf" filters. All but one of the curve fits possessed correlation coefficients (r squared) greater than 0.89, indicating an excellent representation of the data. The MERV 6 curve fit possessed a lower correlation value (0.83) but matched the data well. In all cases, it is not recommended that the curve fits be extrapolated outside of the particle size range used to develop the curve fits (0.03 to 10 µm). These curve fits provide a valuable tool that will enable consumers to accurately estimate the collection efficiency of a filter with a given MERV rating to determine whether its likely performance will justify its increased cost and pressure drop.

Table 6-1. Summary of the Results from the Inert Aerosol Evaluations and Curve Fits of Unaged Unconditioned Air Filters

MERV Rating	Number of Filters Tested	Average Pressure Drop (in. of water gauge) at 370 fpm	Predicted Collection Efficiencies from Curve Fits (%)					
			0.03 µm	0.1 µm	0.3 µm	1.1 µm	3.5 µm	8.4 µm
5	1	0.24	13	0	5	24	34	34
6	2	0.22 ± 0.06	12	6	5	16	35	53
7	6	0.30 ± 0.08	44	13	20	47	61	65
8	4	0.26 ± 0.03	40	20	22	52	75	86
10	1	0.29	55	37	29	53	85	97
12	5	0.46[a] ± 0.09	71	47	49	78	95	99
14	4	0.48[b] ± 0.11	82	59	68	93	99	99
16	3	0.73 ± 0.15	99	95	96	99	99	99

[a] – neglecting electrostatic filter 4FUA-12-3, which had a pressure drop of only 0.13 inches of water gauge
[b] – neglecting filter C6-ADP-15-1, which was evaluated well above its nominal flow rate

6.2 Results from Inert Aerosol Evaluations of "Off-the-Shelf" Electronic Air Cleaners

The measured pressure drops of two of the three tested units (A and P) corresponded well with the information provided by the manufacturers, while the pressure drop for Unit H was nearly double the expected value. However, the measured pressure drops for the EACs averaged 0.14 ± 0.03 inches of water at 370 feet per minute, which is approximately one-half that of the average pressure drop for MERV 5 to 10 filters. In terms of collection efficiency, the MERV ratings that were determined from the tests ranged from one MERV rating below to three MERV ratings above the manufacturer data. The MERV ratings were also consistent with the two samples of each unit that were evaluated. As with the filter testing, the testing during this study consisted of evaluations of pairs of the units; therefore, the results may not be representative of typical performance. (ANSI/ASHRAE 52.2-1999 does not provide any guidance regarding the number of samples of an EAC that should be tested to provide a statistically reasonable representation of their typical performance.)

As with the filters, the collection efficiency curves obtained for the EACs were quite similar in shape. In addition, collection efficiencies measured with the OPC (0.3 to 10 µm) generally corresponded very well with the collection efficiencies measured with the SMPS (0.03 to 0.3 µm). Given that the EACs possessed MERV ratings of 14 and 15, at least initially, they appeared to offer considerably higher collection efficiencies than air filters for a given pressure drop.

As described in Section 5 and Table 5-2, a single curve was fit to all of the "off-the-shelf" EAC results. An excellent correlation between the collected data and the curve fit was obtained (r squared value of 0.96), providing the reader with an excellent tool for predicting the likely collection efficiency of an EAC as a function of particle size.

6.3 Results from Bioaerosol Evaluations of "Off-the-Shelf" Filters and Electronic Air Cleaners

A select group of filters (seven) and EACs (three) were evaluated against a bioaerosol challenge. The purpose of the bioaerosol tests was to compare the penetration of a bioaerosol to the penetration of a similarly sized inert aerosol to determine whether there were any significant differences between the penetration of bioaerosol and inert particles.

Similar to previously reported results (RTI, 2004), in nine of the ten tests, the measured bioaerosol collection efficiencies generally exceeded the average collection efficiency for inert particles with physical particle diameters between 0.3 and 1 µm (E1) but were generally less than or equivalent to the inert aerosol collection efficiency results for 1 to 3 µm particles (E2). For the remaining filter (6DDUE-8), a low (6%) bioaerosol collection efficiency was measured with a significant standard deviation. When the standard deviation is taken into consideration, the test results are likely in reasonable agreement. Overall, the results indicate that bioaerosol particles are collected similarly to comparably sized inert particles.

6.4 Results from Aging Evaluations of "Off-the-Shelf" Filters

For a select group of filters (seven), aging was performed in conjunction with inert aerosol testing to examine the effect of dust loading in actual use environments on the collection efficiencies and pressure drops of the units.

For the two electrostatic residential filters (6DDUE-8 and 8NM-10), the collection efficiencies for larger particles (3.0 to 10.0 µm) either increased significantly (6DDUE-8) or remained the same (8NM-10) after the filters started to be loaded with particles. However, for both filters, a substantial decrease in collection efficiencies was noted for smaller particles (0.3 to 3 µm) after the filters were loaded. The collection efficiencies of the filters for smaller particles did not exceed the initial efficiencies until between 8 and 12 weeks of loading had occurred. The pressure drops of both residential filters remained fairly consistent through the first 8 weeks of use; the pressure drops then increased greatly between Weeks 8 and 12. It should be noted that 12 weeks of use constitutes 100% of the manufacturer-recommended service time for these two filters.

Similarly, the two electrostatic commercial prefilters (C17FPP-8 and C15AAA-11) demonstrated consistent average collection efficiencies over the entire 16-week aging duration for larger particles (4.0 to 10.0 µm). However, there was a very substantial drop in collection efficiencies for particles smaller than approximately 4 µm once the loading began, and the collection efficiencies for the smaller particles never returned to the measured initial values. The pressure drops of the prefilters did not demonstrate any noticeable increase over the aging period. It should be noted that the typical service life for prefilters in the HVAC system of interest range from 3 to 6 months, so the 4 months of aging that was performed represented between 67% and 133% of a typical service period. The performance of Filter C15AAA-11 was considerably poorer than was specified in the manufacturer's literature.

In contrast, the 12-inch deep electrostatic commercial box filter (C8GZ-13) substantially degraded in collection efficiency for all particle sizes over the entire aging period, dropping steadily from MERV 12 to MERV 10. No change in pressure drop occurred over this period, implying that a suitable dust cake did not form during loading, which would likely have caused the degradation of collection efficiency to slow. It should be noted that the typical service life for filter C8GZ-13 in the application of interest is 6 to 12 months, typically closer to 12 months, so the aging period represented only 33% to 67% of the typical service life.

As expected, the two commercial, 12-inch deep, non-electrostatic, traditional fiberglass media deep-pleated filters (C14PCS and C11GM-16) did not demonstrate any degradation in collection efficiencies during the aging period. In fact, the collection efficiency of Filter C14PCS clearly increased as dust was collected on the filter during aging. No change in pressure drops was noted over the aging period for these two filters. The typical service life for these two filters in the application of interest is 6 to 12 months (typically closer to 12 months), so the aging period represented only 33% to 67% of the typical service life.

6.5 Results from Aging Evaluations of "Off-the-Shelf" Electronic Air Cleaners

For a select group of EACs (three), aging was performed in conjunction with inert aerosol testing to examine the effect of dust loading in actual use environments on the collection efficiencies and pressure drops of the units. Cleaning was not performed over the entire aging duration. This was consistent with the manufacturers' recommendations of cleaning intervals between 1 and 6 months in duration. Cleaning was recommended in the manufacturers' literature only when a visible inspection indicated that cleaning was clearly required.

As expected, the pressure drops of all three units remained consistent over the entire aging period. By far, Unit A demonstrated the least degradation in performance over the aging period as it appeared to be operating satisfactorily even after 2,016 hours of use without any maintenance. Although Unit A did decrease from a MERV 15 to a MERV 14 over the aging period, this was due to a minor decrease in the average efficiency for 0.3 to 1 µm particles (from 87.6% to 80.7%), as the efficiencies in the other particle size ranges remained virtually identical.

Unit H also performed reasonably well over the aging period but showed more degradation than Unit A, dropping from a MERV 15 to a MERV 12. However, the MERV rating remained consistent for the first 1,008 hours of aging, even though its average efficiency for 0.3 to 1 µm particles decreased from 93.4% to 86.8% between 336 and 1,008 hours of operation. After 2,016 hours of operation, its average efficiency for 0.3 to 1 µm particles dropped to 74.7% and decreased for larger particles as well. Cleaning of Unit H after 84 days of continuous operation appeared to be warranted.

In contrast, Unit P decreased slightly in collection efficiency for particles smaller than 1 µm between 168 and 336 hours of use and then dropped precipitously from a MERV 14 to a MERV 6 between 336 hours and 1,008 hours of use. Despite the significant drop in collection efficiency for Unit P between 336 hours and 1,008 hours, the visible buildup on the unit was not substantial enough to warrant cleaning. Unit P was not visibly dirtier than the other two units, so the user would have no reason to suspect that performance had substantially degraded. However, based on its collection efficiency, cleaning of Unit P would be recommended after 14 days of continuous use.

6.6 Results from Conditioning Evaluations of "Off-the-Shelf" Filters

Eight electrostatic filters were evaluated using a modified inert aerosol test method that involved conditioning with submicron potassium chloride particles to identify their minimum collection efficiencies, rather than their initial collection efficiencies. This modified inert aerosol test method was performed in accordance with the latest recommendation from ASHRAE, namely draft Addendum C to ANSI/ASHRAE Standard 52.2-1999. The purpose of these tests was to compare the results from the aging and conditioning tests to determine whether draft Addendum C provides a means for accurately simulating the performance of an electrostatic filter in a typical use environment.

Four of the residential electrostatic filters performed similarly during the conditioning evaluations. Upon conditioning, the collection efficiencies increased significantly for particles larger than approximately 1 to 2 µm but appeared to decrease slightly or remain constant for particles smaller than 1 to 2 µm. This was consistent with the observed trend during the aging tests of one of the residential filters, in which the collection efficiency increased upon aging for particles larger than 4 µm but decreased significantly for particles smaller than 2 µm. Aging results were not available for comparison for the remaining three residential filters.

For a fifth residential filter, the collection efficiency decreased slightly for all particles upon initial conditioning but increased for all particles once the equivalent of 1 month of conditioning had been performed. This trend was similar to the results observed during the aging tests, although the decrease was more substantial and required approximately 12 weeks of aging to increase past the initial values.

Similar to those of the residential filters, the aging and conditioning tests of a commercial prefilter appeared to be consistent. Conditioning of the commercial prefilter resulted in a noticeable decrease in collection efficiency for all particles less than approximately 1 µm, with no recovery during the approximately 1 month equivalent of conditioning. Aging of the prefilter also resulted in a decrease (although more substantial) in collection efficiency for all particles smaller than approximately 4 µm, with no recovery over 16 weeks of aging.

In contrast, the aging and conditioning tests of the remaining two commercial filters did not produce consistent results. For a commercial prefilter, the collection efficiency increased slightly for all particles upon initial conditioning and remained at the same level with further conditioning. This result noticeably contrasted with the results from the aging evaluations, in which the collection efficiency decreased substantially for particles smaller than 4 µm with aging and did not increase over 16 weeks of use. For a commercial box filter, the results from the aging and conditioning evaluations contrasted even more strongly. In the conditioning evaluation, the collection efficiency remained essentially constant during the approximately 1 month equivalent of conditioning, even increasing slightly for particles smaller than 0.3 µm. However, during the entire 16 weeks of aging, the box filter consistently and continually decreased in collection efficiency for all particles.

It is not known why the trends in the results from the conditioning evaluations are consistent with the aging results for three of the filters but inconsistent with the aging results for the other two filters. Further investigation of these contrasting results seems warranted but is beyond the scope of the present effort. It should be noted that during the conditioning evaluations, a single filter was used. In contrast, the aging evaluations were performed with five different filters of identical make, model, and size. Therefore, some variability is present in the aging evaluations due to the different performance levels of the individual filters, as well as between the filters used in the conditioning evaluation and the aging evaluations.

6.7 Results from Conditioning Evaluations of "Off-the-Shelf" Electronic Air Cleaners

Three EACs were evaluated both before and after exposure to silicon vapor. The purpose of the exposure to silicon vapor was to compare the results from exposure to silicon vapor to the results from the aging tests to determine whether the silicon vapor exposure resulted in a realistic assessment of the likely performance of the EACs after 1 month of actual use.

The exposure of Units A and P to silicon vapor appeared to cause a very similar degradation to that likely observed after 1 month of ambient aging (672 hours of use). For both of these units, the collection efficiency of the electronic air cleaner degraded more than that observed during 336 hours (2 weeks) of ambient use but less than that observed after 1,008 hours (6 weeks) of ambient use.

For Unit H, however, the silicon vapor exposure degraded the unit's performance well beyond that observed after even 2,016 hours of ambient aging (12 weeks of continuous operation).

It is not known why the results from the aging and conditioning evaluations are consistent for units A and P but inconsistent for Unit H. It could be the result of design and component differences between the three units. Given the approximately 50% decrease in pressure drop in Unit H after silicon vapor exposure, and the alteration in the shape of the collection efficiency curve, it is possible that the exposure allowed leakage to occur within the unit. Further investigation of the contrasting results for Unit H seems warranted but was beyond the scope of this effort.

It should be noted that in contrast to the filter evaluations, during the EAC aging evaluations, a single unit was used. Therefore, no variability was present within the EAC aging evaluations due to the different performance levels of individual units.

6.8 Recommendations

As a result of this effort, curve fits are now available that provide a valuable tool enabling researchers/consumers to accurately estimate the collection efficiency of a filter or EAC (by particle size) with a given MERV rating to determine whether its likely performance will justify its increased cost and pressure drop. Unfortunately, due to a combination of a limited test matrix and some filters that did not perform as anticipated, data for filters performing at MERV ratings of 9, 11, 13, and 15 were not acquired. Therefore, future efforts should be performed to capture data for these MERV ratings. In addition, acquiring additional data for filters with MERV ratings of 5 and 10 is desirable as only one filter was available at that performance rating in the current study.

Also, it was observed during this study that a number of filters did not perform in accordance with the MERV ratings provided by the filter vendors. Although in many cases, the performance was only a few percentage points below the vendor-provided rating, in some cases, the performance was three or four MERV ratings below. The standard for establishing MERV ratings (ANSI/ASHRAE 52.2-1999) does not currently provide any guidance as to the number of samples of a filter type that should be tested to ensure that the manufacturer-reported MERV rating provides a statistically reasonable representation of their performance. Therefore, currently, an evaluation of a single filter could be used to characterize the performance of a very large number of filters. A study investigating the consistency of performance for filters at a given MERV rating is recommended to enable consumers to make better-informed decisions about the likely performance of purchased filters.

In this study, EACs appeared to be an excellent choice for residential air cleaning as they provided substantially higher collection efficiencies than are available from residential filters, at a fraction of the pressure drop. Evaluations of their performance to better define the likely frequency of cleaning and the collection efficiency performance as a function of the number of cleaning cycles are needed to compare the long-term operational costs of EACs to that of air filters.

The results from this study indicated that the conditioning procedures for electrostatic filters described in Addendum C of ANSI/ASHRAE 52.2-1999 warrant additional investigation. Although the results from aging and conditioning via Addendum C demonstrated similar trends for residential electrostatic filters, the results from the commercial filters contrasted strongly.

Similarly, the silicon vapor exposure conditioning method that was investigated for EACs would benefit from additional study. For two of the three units evaluated, the results between the aging and conditioning methodology showed very good agreement; however, for the third unit, the results contrasted significantly.

While these results seem promising for the silicon vapor exposure method, additional study and refinement seem warranted.

For the inert particles, size measurements were made using a light-scattering technique (0.3 to 10 μm) and a technique based on electrical mobility (0.03 to 0.3 μm). In general, the collection efficiency measured at the lowest size bin for the larger range (0.35 μm midpoint) was within 10% of the highest size bin of the smaller size range (0.294 μm midpoint). Often, the agreement was much closer. However, to our knowledge a study to assess the agreement between the two measurement methods in a range of overlapping particle sizes has not been performed. It is recommended that research be performed to investigate the differences between these different measurement techniques in the overlapping size range.

7.0 References

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Appendix A
Sample Calculations from the Inert Aerosol Tests

Table A-1. Example Correlation Ratio Calculation (Filter IPP-6-1)

OPC Channel #	1	2	3	4	5	6	7	8	9	10	11	12
Geo. Mean Dia. (μm)	0.35	0.47	0.62	0.84	1.14	1.44	1.88	2.57	3.46	4.69	6.20	8.37
Upstream – Bkg	22	31	22	49	21	12	34	18	13	13	2	5
Upstream – Bkg	27	70	50	96	29	19	23	32	17	9	2	3
Upstream – Bkg	12	28	18	18	10	5	6	6	5	4	1	3
Upstream – Bkg	4	8	4	6	3	3	5	5	9	4	1	1
Upstream – Bkg	7	6	5	9	0	0	5	2	3	3	0	0
Upstream – Bkg	3	17	11	19	6	8	4	12	6	2	0	1
Upstream	6,057	6,920	3,710	8,115	3,000	1,694	2,389	2,827	1,615	901	235	91
Upstream	6,601	7,633	4,069	8,856	3,256	1,875	2,667	3,186	1,844	1,049	285	116
Upstream	6,812	7,968	4,113	9,175	3,279	1,937	2,758	3,252	1,890	1,116	299	113
Upstream	6,906	8,068	4,145	9,329	3,375	2,004	2,764	3,243	1,881	1,114	305	109
Upstream	7,022	8,022	4,240	9,414	3,458	1,990	2,773	3,242	1,866	1,114	302	118
Upstream	7,174	7,969	4,236	9,583	3,411	1,993	2,769	3,311	1,910	1,093	286	119
Upstream	7,324	8,208	4,279	9,794	3,482	2,095	2,833	3,469	1,985	1,074	304	115
Upstream	7,255	8,322	4,361	9,747	3,558	2,061	2,860	3,406	1,967	1,097	318	115
Upstream	7,299	8,439	4,366	9,905	3,549	2,063	2,882	3,397	1,966	1,114	303	114
Upstream	7,318	8,376	4,344	9,784	3,482	2,029	2,902	3,428	1,984	1,099	295	111
Upstream	7,176	8,167	4,370	9,591	3,461	1,998	2,915	3,398	1,956	1,071	298	117
Upstream – Bkg	16	30	26	50	6	7	9	11	6	2	3	1
Upstream – Bkg	18	35	48	75	23	12	22	40	16	14	7	9
Upstream – Bkg	3	0	1	5	3	2	5	2	4	3	1	0
Upstream – Bkg	14	15	3	13	7	3	9	10	7	4	2	1
Upstream – Bkg	15	21	19	16	9	1	8	6	5	3	2	3
Upstream – Bkg	12	32	13	36	22	11	8	8	1	2	0	1
Average U_b	12.75	24.42	18.33	32.67	11.58	6.92	11.50	12.67	7.67	5.25	1.75	2.33
Std. Dev U_b	7.59	18.33	16.39	29.36	9.56	5.70	9.53	11.90	5.10	4.29	1.91	2.57
$U_{b, ucl}$	17.57	36.06	28.75	51.32	17.66	10.54	17.55	20.23	10.91	7.97	2.97	3.97
Avg. U_c	6,995	8,008	4,203	9,390	3,392	1,976	2,774	3,287	1,896	1,076	293	112
$U_{b, ucl}$/Avg. U_c	0.0025	0.0045	0.0068	0.0055	0.0052	0.0053	0.0063	0.0062	0.0058	0.0074	0.0101	0.0354
Downstream – Bkg	9	14	9	21	5	4	3	0	4	0	0	0
Downstream – Bkg	1	1	1	7	0	1	0	0	0	0	0	0
Downstream – Bkg	3	7	5	11	4	1	5	3	3	1	1	0
Downstream – Bkg	8	21	19	44	12	18	27	22	14	11	1	6
Downstream – Bkg	8	12	10	12	8	3	6	8	4	2	2	0
Downstream – Bkg	3	10	5	9	2	4	2	3	1	2	0	1
Downstream	6,206	6,849	3,638	8,126	3,085	1,696	2,503	2,901	1,672	959	250	103
Downstream	6,543	7,481	3,993	8,798	3,260	1,937	2,580	3,244	1,832	1,031	296	116
Downstream	6,758	7,576	4,028	9,255	3,239	1,913	2,648	3,234	1,863	1,055	296	132
Downstream	7,162	8,011	4,195	9,447	3,445	1,996	2,922	3,304	1,888	1,141	289	112
Downstream	7,155	8,106	4,131	9,281	3,447	2,014	2,818	3,313	1,861	1,080	286	113

Table A-1. Example Correlation Ratio Calculation (Filter IPP-6-1) (continued)

OPC Channel #	1	2	3	4	5	6	7	8	9	10	11	12
Geo. Mean Dia. (μm)	**0.35**	**0.47**	**0.62**	**0.84**	**1.14**	**1.44**	**1.88**	**2.57**	**3.46**	**4.69**	**6.20**	**8.37**
Downstream	7,051	7,978	4,124	9,198	3,394	1,958	2,722	3,298	1,907	1,090	295	104
Downstream	7,158	8,151	4,203	9,406	3,535	2,017	2,919	3,346	1,932	1,112	297	138
Downstream	7,231	8,246	4,385	9,598	3,499	2,093	2,737	3,351	1,859	1,090	307	132
Downstream	7,103	8,176	4,177	9,407	3,371	2,021	2,813	3,221	1,844	1,028	290	133
Downstream	7,356	8,516	4,338	10,027	3,612	2,028	2,960	3,472	2,000	1,105	320	130
Downstream	7,025	7,877	4,222	9,283	3,349	1,935	2,798	3,325	1,881	1,070	291	138
Downstream – Bkg	7	12	5	15	3	2	2	3	2	1	0	0
Downstream – Bkg	2	4	1	7	2	1	1	1	1	0	0	0
Downstream – Bkg	2	0	2	2	2	0	6	2	0	1	0	0
Downstream – Bkg	3	5	6	4	0	1	1	1	0	0	1	0
Downstream – Bkg	2	2	3	1	1	2	4	3	0	0	0	0
Downstream – Bkg	13	10	5	4	6	2	3	2	0	1	0	0
Average D_b	5.08	8.17	5.92	11.42	3.75	3.25	5.00	4.00	2.42	1.58	0.42	0.58
Std. Dev D_b	3.78	6.18	4.98	11.75	3.55	4.81	7.20	6.05	3.96	3.06	0.67	1.73
$D_{b, ucl}$	7.48	12.09	9.08	18.88	6.00	6.30	9.57	7.84	4.94	3.53	0.84	1.68
$D_{b, ucl}$/Avg. U_c	0.0011	0.0015	0.0022	0.0020	0.0018	0.0032	0.0035	0.0024	0.0026	0.0033	0.0029	0.0150
R	0.999	0.989	0.986	0.989	1.001	0.996	1.000	0.999	0.988	0.998	1.004	1.115
Std Dev. R	0.0212	0.0199	0.0167	0.0247	0.0263	0.0211	0.0377	0.0260	0.0290	0.0401	0.0491	0.1131
Std. Dev. R*t/n0.5	0.0142	0.0133	0.0112	0.0166	0.0177	0.0142	0.0253	0.0174	0.0195	0.0269	0.0330	0.0760

Table A-2. Example Penetration Calculation (Filter IPP-6-1)

OPC Channel #	1	2	3	4	5	6	7	8	9	10	11	12
Geo. Mean Dia. (µm)	**0.35**	**0.47**	**0.62**	**0.84**	**1.14**	**1.44**	**1.88**	**2.57**	**3.46**	**4.69**	**6.20**	**8.37**
Upstream – Bkg	167	239	163	248	112	82	84	84	48	18	2	11
Upstream – Bkg	27	36	20	47	13	13	13	15	8	5	1	2
Upstream – Bkg	13	13	10	26	4	11	7	5	0	2	1	0
Upstream – Bkg	4	3	3	2	1	0	2	3	2	0	0	0
Upstream – Bkg	3	17	7	9	5	1	3	3	0	1	1	0
Upstream – Bkg	11	8	3	6	4	1	3	3	0	0	0	0
Upstream	6,034	6,713	3,534	7,736	2,911	1,639	2,111	2,225	1,080	505	120	38
Upstream	6,836	7,655	4,007	8,799	3,310	1,843	2,395	2,604	1,275	564	137	44
Upstream	6,909	7,778	4,085	8,947	3,380	1,915	2,413	2,656	1,302	568	138	40
Upstream	6,804	7,680	4,049	8,942	3,247	1,903	2,379	2,570	1,262	569	123	38
Upstream	6,733	7,650	4,015	8,813	3,175	1,803	2,335	2,523	1,252	556	118	34
Upstream	6,787	7,640	3,940	8,786	3,267	1,770	2,343	2,504	1,261	570	137	42
Upstream	6,936	7,656	4,012	8,874	3,312	1,776	2,349	2,536	1,237	556	145	52
Upstream	7,027	7,784	4,208	8,886	3,375	1,881	2,377	2,571	1,244	549	143	41
Upstream	6,983	7,838	4,220	9,002	3,406	1,940	2,412	2,596	1,307	567	138	37
Upstream	6,972	7,855	4,196	9,163	3,385	1,887	2,415	2,603	1,293	565	136	45
Upstream	6,973	7,833	4,171	9,070	3,322	1,885	2,369	2,573	1,250	568	134	44
Upstream – Bkg	12	9	10	18	8	4	12	8	1	0	1	0
Upstream – Bkg	5	16	8	15	6	6	7	4	2	0	1	0
Upstream – Bkg	6	4	0	5	1	1	1	2	1	0	0	0
Upstream – Bkg	4	4	0	4	2	3	0	2	1	0	0	0
Upstream – Bkg	5	6	6	6	4	2	3	6	0	0	0	0
Upstream – Bkg	4	2	5	9	2	2	2	2	6	4	0	1
Average U_b	21.75	29.75	19.58	32.92	13.50	10.50	11.42	11.42	5.75	2.50	0.58	1.17
Std. Dev U_b	46.24	66.56	45.49	68.90	31.20	22.89	23.24	23.15	13.55	5.18	0.67	3.16
$U_{b,\ ucl}$	51.13	72.04	48.48	76.69	33.32	25.04	26.18	26.13	14.36	5.79	1.01	3.17
Avg. U_t	6,817	7,644	4,040	8,820	3,281	1,840	2,354	2,542	1,251	558	133	41
$U_{b,\ ucl}$/Avg. U_t	0.0075	0.0094	0.0120	0.0087	0.0102	0.0136	0.0111	0.0103	0.0115	0.0104	0.0076	0.0771
Downstream – Bkg	9	3	1	3	1	2	4	7	2	0	0	0
Downstream – Bkg	5	8	5	10	2	5	1	0	1	0	0	0
Downstream – Bkg	4	0	0	2	0	1	0	0	0	0	0	0
Downstream – Bkg	5	7	4	6	1	1	3	1	0	0	0	0
Downstream – Bkg	14	4	3	2	0	0	0	1	0	0	0	0
Downstream – Bkg	6	3	1	0	0	1	1	2	0	0	0	0
Downstream	5,655	6,366	3,420	6,695	2,288	1,161	1,346	1,325	727	330	94	25
Downstream	6,569	7,358	3,873	7,574	2,502	1,253	1,526	1,601	765	404	91	25
Downstream	6,727	7,461	3,800	7,679	2,571	1,315	1,541	1,603	830	372	92	31
Downstream	6,470	7,205	3,825	7,618	2,533	1,249	1,476	1,472	789	361	81	28

Table A-2. Example Penetration Calculation (Filter IPP-6-1) (continued)

OPC Channel #	1	2	3	4	5	6	7	8	9	10	11	12
Geo. Mean Dia. (μm)	**0.35**	**0.47**	**0.62**	**0.84**	**1.14**	**1.44**	**1.88**	**2.57**	**3.46**	**4.69**	**6.20**	**8.37**
Downstream	6,310	6,957	3,646	7,256	2,397	1,192	1,397	1,383	704	363	89	22
Downstream	6,541	7,565	3,746	7,600	2,529	1,283	1,528	1,488	773	387	78	41
Downstream	6,606	7,273	3,635	7,447	2,454	1,245	1,427	1,460	745	346	92	35
Downstream	6,912	7,855	3,930	8,119	2,686	1,374	1,502	1,610	792	387	105	37
Downstream	6,983	7,828	3,980	8,035	2,655	1,359	1,511	1,633	872	351	116	36
Downstream	6,675	7,395	3,792	7,773	2,486	1,237	1,495	1,465	735	359	101	24
Downstream	6,783	7,589	3,965	7,702	2,486	1,247	1,470	1,459	787	388	81	26
Downstream – Bkg	6	3	2	7	1	1	1	3	1	1	0	0
Downstream – Bkg	6	5	4	7	0	2	1	2	0	0	0	0
Downstream – Bkg	5	5	3	6	0	1	0	0	0	0	0	0
Downstream – Bkg	6	1	1	2	1	1	0	0	0	0	0	0
Downstream – Bkg	6	2	2	3	1	0	0	0	0	0	0	0
Downstream – Bkg	8	4	6	3	0	0	1	1	0	0	0	0
Average D_b	6.67	3.75	2.67	4.25	0.58	1.25	1.00	1.42	0.33	0.08	0.00	0.00
Std. Dev D_b	2.67	2.30	1.83	2.90	0.67	1.36	1.28	2.02	0.65	0.29	0.00	0.00
$D_{b,\,ucl}$	8.37	5.21	3.83	6.09	1.01	2.11	1.81	2.70	0.75	0.27	0.00	0.00
$D_{b,\,ucl}$/Avg. U_t	0.0012	0.0007	0.0009	0.0007	0.0003	0.0011	0.0008	0.0011	0.0006	0.0005	0.0000	0.0000
$P_{observed}$	0.9649	0.9646	0.9408	0.8635	0.7677	0.6912	0.6290	0.5922	0.6223	0.6629	0.6998	0.7558
Std Dev. $P_{observed}$	0.0190	0.0292	0.0231	0.0248	0.0199	0.0275	0.0154	0.0269	0.0356	0.0326	0.0828	0.1634
R (from Table A-1)	0.999	0.989	0.986	0.989	1.001	0.996	1.000	0.999	0.988	0.998	1.004	1.115
$P_{corrected}$	0.9657	0.9751	0.9544	0.8735	0.7670	0.6938	0.6289	0.5925	0.6296	0.6641	0.6972	0.6779
Filtration Efficiency (%)	3.4	2.5	4.6	12.7	23.3	30.6	37.1	40.8	37.0	33.6	30.3	32.2

Appendix B
Sample Calculations from the Bioaerosol Tests

Table B-1. Example Bioaerosol P_{100} Calculation (820 cfm flow rate) with no filter in the system

Sample	CFU mL in sample	Total CFU in sample	Sampling flow rate (lpm)	Sampling Duration (min)	CFU/liter of air	Average Concentration (CFU/liter of air)	Std. Dev.	Coefficent of Variance
Upstream	$4.23*10^4$	$4.23*10^5$	7.342	10	$5.76*10^3$	$5.24*10^3$	$5.3*10^2$	10%
Upstream	$4.18*10^4$	$4.18*10^5$	7.368	10	$5.68*10^3$			
Upstream	$4.15*10^4$	$4.15*10^5$	7.380	10	$5.63*10^3$			
Upstream	$3.43*10^4$	$3.43*10^5$	7.275	10	$4.72*10^3$			
Upstream	$3.35*10^4$	$3.35*10^5$	7.347	10	$4.56*10^3$			
Upstream	$3.78*10^4$	$3.78*10^5$	7.271	10	$5.20*10^3$			
Upstream	$3.49*10^4$	$3.49*10^5$	7.420	10	$4.70*10^3$			
Upstream	$3.63*10^4$	$3.63*10^5$	7.325	10	$4.96*10^3$			
Upstream	$4.26*10^4$	$4.26*10^5$	7.164	10	$5.95*10^3$			
Downstream	$3.87*10^4$	$3.87*10^5$	7.211	10	$5.37*10^3$	$5.21*10^3$	$3.7*10^2$	7%
Downstream	$3.88*10^4$	$3.88*10^5$	7.439	10	$5.22*10^3$			
Downstream	$3.86*10^4$	$3.86*10^5$	7.415	10	$5.21*10^3$			
Downstream	$3.95*10^4$	$3.95*10^5$	7.415	10	$5.33*10^3$			
Downstream	$4.05*10^4$	$4.05*10^5$	7.602	10	$5.33*10^3$			
Downstream	$4.20*10^4$	$4.20*10^5$	7.321	10	$5.74*10^3$			
Downstream	$3.56*10^4$	$3.56*10^5$	7.362	10	$4.84*10^3$			
Downstream	$3.22*10^4$	$3.22*10^5$	7.257	10	$4.44*10^3$			
Downstream	$3.94*10^4$	$3.94*10^5$	7.234	10	$5.45*10^3$			
Background	$<2*10^1$	$<2*10^2$	~7.4	10	<2.7			
Background	$<2*10^1$	$<2*10^2$	~7.2	10	<2.8			
$P_{measured}$						0.995		

Table B-2. Example Bioaerosol Calculation (Filter 8NM-10-12)

Sample	CFU/ mL in sample	Total CFU in sample	Sampling flow rate (lpm)	Sampling Duration (min)	CFU/liter of air	Average Concentration (CFU/liter of air)	Std. Dev.	Coefficient of Variance
Upstream	$4.02*10^4$	$4.02*10^5$	7.468	10	$5.38*10^3$	$4.91*10^3$	$4.40*10^2$	9%
Upstream	$3.44*10^4$	$3.44*10^5$	7.496	10	$4.59*10^3$			
Upstream	$4.26*10^4$	$4.26*10^5$	7.417	10	$5.75*10^3$			
Upstream	$3.68*10^4$	$3.68*10^5$	7.348	10	$5.01*10^3$			
Upstream	$3.43*10^4$	$3.43*10^5$	7.443	10	$4.61*10^3$			
Upstream	$3.52*10^4$	$3.52*10^5$	7.358	10	$4.78*10^3$			
Upstream	$3.64*10^4$	$3.64*10^5$	7.534	10	$4.83*10^3$			
Upstream	$3.20*10^4$	$3.20*10^5$	7.476	10	$4.28*10^3$			
Upstream	$3.59*10^4$	$3.59*10^5$	7.298	10	$4.92*10^3$			
Downstream	$2.18*10^4$	$2.18*10^5$	7.355	10	$2.97*10^3$	$2.93*10^3$	$1.68*10^2$	6%
Downstream	$2.19*10^4$	$2.19*10^5$	7.601	10	$2.88*10^3$			
Downstream	$2.13*10^4$	$2.13*10^5$	7.564	10	$2.82*10^3$			
Downstream	$1.99*10^4$	$1.99*10^5$	7.571	10	$2.62*10^3$			
Downstream	$2.24*10^4$	$2.24*10^5$	7.677	10	$2.92*10^3$			
Downstream	$2.19*10^4$	$2.19*10^5$	7.467	10	$2.93*10^3$			
Downstream	$2.17*10^4$	$2.17*10^5$	7.488	10	$2.90*10^3$			
Downstream	$2.37*10^4$	$2.37*10^5$	7.376	10	$3.21*10^3$			
Downstream	$2.30*10^4$	$2.30*10^5$	7.365	10	$3.12*10^3$			
Background	$<2*10^1$	$<2*10^2$	7.564	10	<2.7			
Background	$<2*10^1$	$<2*10^2$	7.358	10	<2.8			
$P_{measured}$						0.597		
P_{100} (from Table B-1)						0.995		
$P_{corrected}$						0.600		
Filtration Efficiency						40%		
Combined Standard Deviation						6%		

Appendix C
Additional Information on Aging of Filters During the In-Use Tests

Figure C-1. Photograph of Residential HVAC System Used to Age Filter 6DDUE-8

Table C-1. Basic Information on Residential HVAC System Used to Age Filter 6DDUE-8

Approximate House Size (sq. ft)	~2,200 sq. ft.
HVAC System Make/Model	Atlas Butler
Approximate Age of HVAC System	1 year
Type of Flooring	Carpet
Number and Type of Pets	1 mid-size dog
Number of Adults/Kids in Household	2 adults/0 children

Figure C-2. Photograph of Residential HVAC System Used to Age Filter 8NM-10

Table C-2. Basic Information on Residential HVAC System Used to Age Filter 8NM-10

Approximate House Size (sq. ft)	2,800 sq ft.
HVAC System Make/Model	Carrier
Approximate Age of HVAC System	33 years
Type of Flooring	Carpet
Number and Type of Pets	None
Number of Adults/Kids in Household	2 adults/3 children

Figure C-3. Photograph of 40-Filter Commercial HVAC System Used to Age Filters C17FPP-8, C15AAA-11, and C8GZ-13

(C8GZ-13 Filters were inserted behind the prefilters in the gaps shown.)

Figure C-4. Photograph of 40-Filter Commercial HVAC System Used to Age Filters C17FPP-8, C15AAA-11, and C8GZ-13

(The five C17FPP-8 and five C15AAA-11 filters are in the center.)

Figure C-5. Photograph of the 9-Filter Commercial HVAC System Used to Age Filters C14PCS and C11GM-16

(The test filters are shown before the prefilters were installed.)

Figure C-6. Photograph of the 9-Filter Commercial HVAC System Used to Age Filters C14PCS and C11GM-16

(The test filters are behind the prefilters.)

Appendix D
Photographs of the Various Test Systems Utilized During Inert Aerosol Testing, Bioaerosol Testing, Aging of Electronic Air Cleaners, and Exposure of Electronic Air Cleaners

Figure D-1. Photograph of the Upstream Side of Intertek's ASHRAE 52.2-1999 Inert Aerosol Test System Used During the Inert Aerosol Tests and Electrostatic Conditioning Tests

Figure D-2. Photograph of the Downstream Side of Intertek's ASHRAE 52.2-1999 Inert Aerosol Test System Used During the Inert Aerosol Tests and Electrostatic Conditioning Tests

Figure D-3. Photograph of the Test Fixture Used During the Bioaerosol Tests

Figure D-4. Photograph of the Air Intake of the Bioaerosol Test Fixture

Figure D-5. Photograph (side view) of the Test Fixture Used During the Silicon Vapor Exposures of the Electronic Air Cleaners

Figure D-6. Photograph (interior) of the Test Fixture Used During the Silicon Vapor Exposures of the Electronic Air Cleaners

Figure D-7. Photograph of the Downstream Side and Blower of the Test Fixture Used During the Ambient Aging of the Electronic Air Cleaners

Figure D-8. Photograph of the Upstream Side of the Test Fixture and Air Flow Controllers Used During the Ambient Aging of the Electronic Air Cleaners

Appendix E
Results from the Inert Aerosol Evaluations of "Off-The-Shelf" Air Cleaners

Table E-1. Initial Measured Collection Efficiency and Pressure Drop of a Residential 16" x 25" x 1" Pleated Non-Electrostatic Filter (IPP-6-1)

Particle Size Range or Midpoint of Range (μm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	7.6	430	155	0.08	0.07 @ 147 fpm
0.034	8.6	625	225	0.12	0.13 @ 221 fpm
0.039	2.2	833	300	0.18	0.18 @ 295 fpm
0.045	3.1	1,041	375	0.24	0.25 @ 368 fpm
0.052	3.8				
0.060	1.1				
0.070	0				
0.081	2.0				
0.093	0				
0.11	0				
0.12	1.8				
0.14	2.7				
0.17	0.9				
0.19	2.7				
0.22	0				
0.26	0				
0.29	0				
0.30 – 0.40	3.4				
0.40 – 0.55	2.5				
0.55 – 0.70	4.6				
0.70 – 1.00	12.7				
1.00 – 1.30	23.3				
1.30 – 1.60	30.6				
1.60 – 2.20	37.1				
2.20 – 3.00	40.8				
3.00 – 4.00	37				
4.00 – 5.50	33.6				
5.50 – 7.00	30.3				
7.00 – 10.00	32.2				
E1 (0.30 – 1.0)	5.8				
E2 (1.0 – 3.0)	33.0				
E3 (3.0 – 10.0)	33.3				
MERV rating from vendor	6				
MERV rating from testing	5				

Table E-2. Initial Measured Collection Efficiency and Pressure Drop of a Residential 16" x 25" x 1" Pleated Non-Electrostatic Filter (2NS-8-1)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	1.7	410	148	0.07	NA
0.034	2.2	615	221	0.13	NA
0.039	0.0	820	295	0.19	NA
0.045	0.4	1025	369	0.26	NA
0.052	0.7				
0.060	0.5				
0.070	0.4				
0.081	0.0				
0.093	0.9				
0.11	4.8				
0.12	0.4				
0.14	1.9				
0.17	0.0				
0.19	1.0				
0.22	4.8				
0.26	1.9				
0.29	5.1				
0.30 – 0.40	8.0				
0.40 – 0.55	9.7				
0.55 – 0.70	4.9				
0.70 – 1.00	0.8				
1.00 – 1.30	5.0				
1.30 – 1.60	8.3				
1.60 – 2.20	18.2				
2.20 – 3.00	31.1				
3.00 – 4.00	39.2				
4.00 – 5.50	43.0				
5.50 – 7.00	42.6				
7.00 – 10.00	40.4				
E1 (0.30 – 1.0)	5.9				
E2 (1.0 – 3.0)	15.7				
E3 (3.0 – 10.0)	41.3				
MERV rating from vendor	8				
MERV rating from testing	6				

Table E-3. Initial Measured Collection Efficiency and Pressure Drop of a Residential 16" x 25" x 1" Pleated Electrostatic Filter (3PAF-11-1)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	44.2	410	148	0.04	NA
0.034	42.8	615	221	0.12	NA
0.039	42.6	820	295	0.18	0.20 @ 306 fpm
0.045	40.1	1,025	369	0.26	0.32 @ 504 fpm
0.052	37.0				
0.060	34.8				
0.070	33.2				
0.081	31.2				
0.093	29.2				
0.11	28.0				
0.12	27.8				
0.14	26.1				
0.17	26.2				
0.19	23.6				
0.22	24.1				
0.26	25.9				
0.29	26.0				
0.30 – 0.40	23.1				
0.40 – 0.55	24.5				
0.55 – 0.70	23.3				
0.70 – 1.00	22.4				
1.00 – 1.30	26.3				
1.30 – 1.60	30.6				
1.60 – 2.20	39.8				
2.20 – 3.00	55.1				
3.00 – 4.00	68.0				
4.00 – 5.50	79.6				
5.50 – 7.00	88.5				
7.00 – 10.00	92.5				
E1 (0.30 – 1.0)	23.3				
E2 (1.0 – 3.0)	37.9				
E3 (3.0 – 10.0)	82.1				
MERV rating from vendor	11				
MERV rating from testing	8				

Table E-4. Initial Measured Collection Efficiency and Pressure Drop of a Residential 16" x 25" x 1" Pleated Electrostatic Filter (4FUA-12-1)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	48.3	410	148	0.04	NA
0.034	50.8	615	221	0.07	NA
0.039	49.3	820	295	0.09	NA
0.045	48.2	1,025	369	0.13	NA
0.052	46.0				
0.060	43.9				
0.070	42.1				
0.081	40.7				
0.093	40.1				
0.11	38.3				
0.12	36.5				
0.14	34.8				
0.17	33.0				
0.19	32.0				
0.22	34.7				
0.26	32.4				
0.29	34.8				
0.30 – 0.40	30.4				
0.40 – 0.55	32.1				
0.55 – 0.70	41.2				
0.70 – 1.00	55.0				
1.00 – 1.30	69.8				
1.30 – 1.60	77.7				
1.60 – 2.20	86.2				
2.20 – 3.00	89.5				
3.00 – 4.00	90.4				
4.00 – 5.50	90.4				
5.50 – 7.00	93.3				
7.00 – 10.00	94.3				
E1 (0.30 – 1.0)	39.7				
E2 (1.0 – 3.0)	80.8				
E3 (3.0 – 10.0)	92.1				
MERV rating from vendor	12				
MERV rating from testing	12				

Table E-5. Initial Measured Collection Efficiency and Pressure Drop of a Residential 16" x 25" x 1" Pleated Electrostatic Filter (5RM-11-1)

Particle Size Range or Midpoint of Range (μm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	35.5	410	148	0.10	0.06 @ 125 fpm
0.034	31.8	615	221	0.17	0.12 @ 250 fpm
0.039	27.5	820	295	0.25	NA
0.045	26.5	1,025	369	0.34	0.19 @ 375 fpm
0.052	23.6				
0.060	22.3				
0.070	19.7				
0.081	17.5				
0.093	16.0				
0.11	15.7				
0.12	14.9				
0.14	11.8				
0.17	12.3				
0.19	9.4				
0.22	12.6				
0.26	8.7				
0.29	15.7				
0.30 – 0.40	14.7				
0.40 – 0.55	11.7				
0.55 – 0.70	17.1				
0.70 – 1.00	33.3				
1.00 – 1.30	52.9				
1.30 – 1.60	62.5				
1.60 – 2.20	71.2				
2.20 – 3.00	72.9				
3.00 – 4.00	69.4				
4.00 – 5.50	66.5				
5.50 – 7.00	68.2				
7.00 – 10.00	70.4				
E1 (0.30 – 1.0)	19.2				
E2 (1.0 – 3.0)	64.9				
E3 (3.0 – 10.0)	68.7				
MERV rating from vendor	11				
MERV rating from testing	7				

Table E-6. Initial Measured Collection Efficiency and Pressure Drop of a Residential 16" x 25" x 1" Pleated Electrostatic Filter (6DDUE-8)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	25.0	410	148	0.06	0.07 @ 148 fpm
0.034	33.8	615	221	0.10	0.12 @ 221 fpm
0.039	30.8	820	295	0.14	0.17 @ 295 fpm
0.045	28.0	1,025	369	0.19	0.23 @ 369 fpm
0.052	27.1				
0.060	25.7				
0.070	23.0				
0.081	22.3				
0.093	22.3				
0.11	23.6				
0.12	23.3				
0.14	23.2				
0.17	21.8				
0.19	25.4				
0.22	25.3				
0.26	18.2				
0.29	18.1				
0.30 – 0.40	16.1				
0.40 – 0.55	14.0				
0.55 – 0.70	21.4				
0.70 – 1.00	31.1				
1.00 – 1.30	44.8				
1.30 – 1.60	50.6				
1.60 – 2.20	55.6				
2.20 – 3.00	56.8				
3.00 – 4.00	57.6				
4.00 – 5.50	55.5				
5.50 – 7.00	59.2				
7.00 – 10.00	54.9				
E1 (0.30 – 1.0)	20.6				
E2 (1.0 – 3.0)	51.9				
E3 (3.0 – 10.0)	56.8				
MERV rating from vendor	8				
MERV rating from testing	7				

Table E-7. Initial Measured Collection Efficiency and Pressure Drop of a Residential 16" x 25" x 1" Pleated Electrostatic Filter (7AST-8-3)

Particle Size Range or Midpoint of Range (μm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	37.2	410	148	0.11	NA
0.034	36.6	615	221	0.19	NA
0.039	33.7	820	295	0.29	NA
0.045	31.8	1,025	369	0.41	NA
0.052	30.3				
0.060	28.6				
0.070	26.7				
0.081	23.9				
0.093	22.6				
0.11	22.8				
0.12	20.4				
0.14	20.5				
0.17	22.5				
0.19	21.6				
0.22	21.0				
0.26	23.8				
0.29	18.3				
0.30 – 0.40	9.4				
0.40 – 0.55	10.8				
0.55 – 0.70	19.6				
0.70 – 1.00	36.2				
1.00 – 1.30	54.2				
1.30 – 1.60	61.7				
1.60 – 2.20	67.5				
2.20 – 3.00	66.9				
3.00 – 4.00	64.2				
4.00 – 5.50	60.4				
5.50 – 7.00	62.9				
7.00 – 10.00	57.8				
E1 (0.30 – 1.0)	19.0				
E2 (1.0 – 3.0)	62.6				
E3 (3.0 – 10.0)	61.3				
MERV rating from vendor	8				
MERV rating from testing	7				

Table E-8. Initial Measured Collection Efficiency and Pressure Drop of a Residential 16" x 25" x 1" Pleated Electrostatic Filter (8NM-10)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	22.7	410	148	0.17	NA
0.034	20.2	615	221	0.29	NA
0.039	18.5	820	295	0.43	NA
0.045	17.9	1,025	369	0.59	NA
0.052	15.5				
0.060	13.8				
0.070	13.1				
0.081	13.1				
0.093	11.8				
0.11	10.8				
0.12	9.4				
0.14	10.6				
0.17	10.0				
0.19	7.9				
0.22	13.6				
0.26	12.6				
0.29	18.0				
0.30 – 0.40	16.9				
0.40 – 0.55	20.5				
0.55 – 0.70	33.8				
0.70 – 1.00	53.7				
1.00 – 1.30	72.4				
1.30 – 1.60	80.4				
1.60 – 2.20	86.8				
2.20 – 3.00	89.8				
3.00 – 4.00	91.0				
4.00 – 5.50	91.5				
5.50 – 7.00	91.3				
7.00 – 10.00	91.8				
E1 (0.30 – 1.0)	31.2				
E2 (1.0 – 3.0)	82.4				
E3 (3.0 – 10.0)	91.4				
MERV rating from vendor	10				
MERV rating from testing	12				

Table E-9. Initial Measured Collection Efficiency and Pressure Drop of a Commercial 24" x 24" x 2" Pleated Non-Electrostatic Filter (C1APP-7)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	22.1	984	246	0.10	NA
0.034	19.5	1,476	369	0.18	0.12 @ 300 fpm
0.039	18.1	1,968	492	0.28	0.28 @ 500 fpm
0.045	15.4	2,460	615	0.41	0.43 @ 625 fpm
0.052	13.7				
0.060	13.3				
0.070	12.6				
0.081	10.2				
0.093	10.0				
0.11	11.6				
0.12	8.7				
0.14	12.1				
0.17	9.9				
0.19	12.9				
0.22	11.6				
0.26	12.7				
0.29	16.4				
0.30 – 0.40	1.7				
0.40 – 0.55	4.5				
0.55 – 0.70	2.2				
0.70 – 1.00	9.2				
1.00 – 1.30	15.5				
1.30 – 1.60	18.7				
1.60 – 2.20	26.0				
2.20 – 3.00	37.2				
3.00 – 4.00	44.8				
4.00 – 5.50	48.8				
5.50 – 7.00	53.1				
7.00 – 10.00	52.2				
E1 (0.30 – 1.0)	4.4				
E2 (1.0 – 3.0)	24.3				
E3 (3.0 – 10.0)	49.7				
MERV rating from vendor	7				
MERV rating from testing	6				

Table E-10. Initial Measured Collection Efficiency and Pressure Drop of a Commercial 24" x 24" x 2" Non-Pleated Non-Electrostatic Filter (C2T90-8)

Particle Size Range or Midpoint of Range (μm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	0.0[a]	984	246	0.15	NA
0.034	0.0[a]	1,476	369	0.27	0.25 @ 300 fpm
0.039	0.0[a]	1,968	492	0.41	0.50 @ 500 fpm
0.045	0.0[a]	2,460	615	0.57	NA
0.052	0.0[a]				
0.060	0.0[a]				
0.070	0.0[a]				
0.081	0.0[a]				
0.093	0.0[a]				
0.11	0.0[a]				
0.12	0.0[a]				
0.14	0.0[a]				
0.17	0.0[a]				
0.19	0.0[a]				
0.22	0.0[a]				
0.26	0.0[a]				
0.29	0.0[a]				
0.30 – 0.40	5.4				
0.40 – 0.55	10.4				
0.55 – 0.70	17.7				
0.70 – 1.00	26.4				
1.00 – 1.30	32.3				
1.30 – 1.60	38.1				
1.60 – 2.20	48.1				
2.20 – 3.00	61.3				
3.00 – 4.00	63.8				
4.00 – 5.50	56.7				
5.50 – 7.00	50.0				
7.00 – 10.00	35.2				
E1 (0.30 – 1.0)	15.0				
E2 (1.0 – 3.0)	44.9				
E3 (3.0 – 10.0)	51.4				
MERV rating from vendor	8				
MERV rating from testing	7				

[a] – No appreciable collection efficiency was measured in three separate tests.

Table E-11. Initial Measured Collection Efficiency and Pressure Drop of a Commercial 24" x 24" x 4" Pleated Non-Electrostatic Box Filter (C3AV-11)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	59.5	984	246	0.16	0.16 @ 250 fpm
0.034	56.0	1,476	369	0.29	0.29 @ 375 fpm
0.039	53.1	1,968	492	0.46	0.45 @ 500 fpm
0.045	47.9	2,460	615	0.65	0.63 @ 625 fpm
0.052	43.6				
0.060	41.2				
0.070	38.5				
0.081	36.5				
0.093	37.0				
0.11	35.4				
0.12	36.2				
0.14	34.0				
0.17	35.6				
0.19	36.1				
0.22	36.6				
0.26	36.3				
0.29	37.5				
0.30 – 0.40	25.0				
0.40 – 0.55	33.2				
0.55 – 0.70	34.2				
0.70 – 1.00	45.0				
1.00 – 1.30	52.2				
1.30 – 1.60	55.3				
1.60 – 2.20	61.0				
2.20 – 3.00	77.6				
3.00 – 4.00	86.1				
4.00 – 5.50	91.6				
5.50 – 7.00	95.7				
7.00 – 10.00	96.4				
E1 (0.30 – 1.0)	34.3				
E2 (1.0 – 3.0)	61.5				
E3 (3.0 – 10.0)	92.5				
MERV rating from vendor	11				
MERV rating from testing	10				

Table E-12. Initial Measured Collection Efficiency and Pressure Drop of a Commercial 24" x 24" x 12" Pleated Non-Electrostatic Filter (C4FPC-11)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	41.7	984	246	0.13	0.15 @ 250 fpm
0.034	36.6	1,476	369	0.23	0.20 @ 375 fpm
0.039	30.3	1,968	492	0.36	0.30 @ 500 fpm
0.045	27.4	2,460	615	0.52	0.40 @ 625 fpm
0.052	23.1				
0.060	23.3				
0.070	17.9				
0.081	17.1				
0.093	14.6				
0.11	14.0				
0.12	12.9				
0.14	12.6				
0.17	14.8				
0.19	11.3				
0.22	13.5				
0.26	11.0				
0.29	15.9				
0.30 – 0.40	20.6				
0.40 – 0.55	25.5				
0.55 – 0.70	24.6				
0.70 – 1.00	32.2				
1.00 – 1.30	37.3				
1.30 – 1.60	38.8				
1.60 – 2.20	41.8				
2.20 – 3.00	57.1				
3.00 – 4.00	67.9				
4.00 – 5.50	75.4				
5.50 – 7.00	83.7				
7.00 – 10.00	88.4				
E1 (0.30 – 1.0)	25.7				
E2 (1.0 – 3.0)	43.7				
E3 (3.0 – 10.0)	78.9				
MERV rating from vendor	11				
MERV rating from testing	8				

Table E-13. Initial Measured Collection Efficiency and Pressure Drop of a Commercial 24" x 24" x 12" Pleated Non-Electrostatic Filter (C5PSC-11)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	77.1	984	246	0.25	NA
0.034	74.0	1,476	369	0.43	NA
0.039	69.4	1,968	492	0.64	0.60 @ 500 fpm
0.045	66.9	2,460	615	0.90	NA
0.052	62.7				
0.060	59.3				
0.070	55.4				
0.081	52.9				
0.093	50.7				
0.11	49.8				
0.12	48.5				
0.14	48.5				
0.17	48.7				
0.19	50.2				
0.22	51.9				
0.26	51.1				
0.29	51.2				
0.30 – 0.40	49.0				
0.40 – 0.55	56.5				
0.55 – 0.70	62.8				
0.70 – 1.00	71.0				
1.00 – 1.30	75.5				
1.30 – 1.60	80.4				
1.60 – 2.20	85.9				
2.20 – 3.00	92.4				
3.00 – 4.00	95.0				
4.00 – 5.50	97.0				
5.50 – 7.00	98.0				
7.00 – 10.00	99.0				
E1 (0.30 – 1.0)	59.8				
E2 (1.0 – 3.0)	83.6				
E3 (3.0 – 10.0)	97.2				
MERV rating from vendor	13				
MERV rating from testing	12				

Table E-14. Initial Measured Collection Efficiency and Pressure Drop of a Commercial 24" x 24" x 10" 6-Pocket Non-Electrostatic Bag Filter (C6ADP-15)

Particle Size Range or Midpoint of Range (μm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.) (based on 24" x 24" x 30" filter with 8 pockets)
0.029	75.9	984	246	0.77	0.68 @ 250 fpm
0.034	75.1	1,476	369	1.21	1.10 @ 375 fpm
0.039	73.9	1,968	492	1.68	1.48 @ 500 fpm
0.045	72.7	2,460	615	2.18	1.76 @ 560 fpm
0.052	70.8				
0.060	68.9				
0.070	66.6				
0.081	65.1				
0.093	63.1				
0.11	61.8				
0.12	61.9				
0.14	61.0				
0.17	60.0				
0.19	60.2				
0.22	61.9				
0.26	63.4				
0.29	62.1				
0.30 – 0.40	68.0				
0.40 – 0.55	80.0				
0.55 – 0.70	86.5				
0.70 – 1.00	93.9				
1.00 – 1.30	96.6				
1.30 – 1.60	97.7				
1.60 – 2.20	98.6				
2.20 – 3.00	99.3				
3.00 – 4.00	99.4				
4.00 – 5.50	99.2				
5.50 – 7.00	99.5				
7.00 – 10.00	99.5				
E1 (0.30 – 1.0)	82.1				
E2 (1.0 – 3.0)	98.1				
E3 (3.0 – 10.0)	99.4				
MERV rating from vendor	14				
MERV rating from testing	14				

Table E-15. Initial Measured Collection Efficiency and Pressure Drop of a Commercial 24" x 24" x 12" Pleated Electrostatic Box Filter (C7CFER-13)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	86.5	984	246	0.38	0.22 @ 250 fpm
0.034	83.7	1,476	369	0.60	0.38 @ 375 fpm
0.039	80.0	1,968	492	0.85	0.58 @ 500 fpm
0.045	77.6	2,460	615	1.12	0.80 @ 625 fpm
0.052	75.2				
0.060	71.8				
0.070	68.5				
0.081	66.6				
0.093	65.0				
0.11	63.7				
0.12	62.8				
0.14	62.9				
0.17	63.1				
0.19	63.4				
0.22	64.9				
0.26	65.9				
0.29	67.7				
0.30 – 0.40	69.7				
0.40 – 0.55	79.2				
0.55 – 0.70	84.3				
0.70 – 1.00	91.0				
1.00 – 1.30	94.1				
1.30 – 1.60	95.9				
1.60 – 2.20	97.7				
2.20 – 3.00	99.3				
3.00 – 4.00	99.7				
4.00 – 5.50	99.7				
5.50 – 7.00	99.8				
7.00 – 10.00	99.8				
E1 (0.30 – 1.0)	81.1				
E2 (1.0 – 3.0)	96.8				
E3 (3.0 – 10.0)	99.8				
MERV rating from vendor	14				
MERV rating from testing	14				

Table E-16. Initial Measured Collection Efficiency and Pressure Drop of a Commercial 24" x 24" x 12" Pleated Electrostatic Box Filter (C8GZ-13) (Test #1)

Particle Size Range or Midpoint of Range (μm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	74.8	984	246	0.25	NA
0.034	73.0	1,476	369	0.40	NA
0.039	72.9	1,968	492	0.59	0.44 @ 500 fpm
0.045	73.2	2,460	615	0.80	NA
0.052	72.2				
0.060	70.8				
0.070	69.6				
0.081	68.2				
0.093	68.8				
0.11	66.1				
0.12	65.4				
0.14	65.4				
0.17	64.7				
0.19	63.7				
0.22	63.2				
0.26	63.2				
0.29	60.3				
0.30 – 0.40	60.9				
0.40 – 0.55	66.4				
0.55 – 0.70	72.5				
0.70 – 1.00	77.7				
1.00 – 1.30	82.3				
1.30 – 1.60	85.5				
1.60 – 2.20	90.1				
2.20 – 3.00	95.2				
3.00 – 4.00	97.3				
4.00 – 5.50	98.5				
5.50 – 7.00	99.2				
7.00 – 10.00	99.6				
E1 (0.30 – 1.0)	69.4				
E2 (1.0 – 3.0)	88.3				
E3 (3.0 – 10.0)	98.6				
MERV rating from vendor	13				
MERV rating from testing	12				

Table E-17. Initial Measured Collection Efficiency and Pressure Drop of a Commercial 24" x 24" x 12" Pleated Electrostatic Box Filter (C8GZ-13) (Test #2)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	65.5	984	246	0.26	NA
0.034	64.7	1,476	369	0.43	NA
0.039	60.1	1,968	492	0.63	0.44 @ 500 fpm
0.045	61.5	2,460	615	0.89	NA
0.052	58.3				
0.060	59.4				
0.070	58.8				
0.081	55.4				
0.093	56.3				
0.11	53.6				
0.12	53.8				
0.14	52.0				
0.17	52.5				
0.19	53.7				
0.22	50.4				
0.26	53.4				
0.29	53.9				
0.30 – 0.40	66.3				
0.40 – 0.55	73.8				
0.55 – 0.70	81.7				
0.70 – 1.00	88.3				
1.00 – 1.30	94.0				
1.30 – 1.60	96.1				
1.60 – 2.20	97.2				
2.20 – 3.00	97.9				
3.00 – 4.00	98.2				
4.00 – 5.50	98.4				
5.50 – 7.00	98.2				
7.00 – 10.00	100.0				
E1 (0.30 – 1.0)	77.5				
E2 (1.0 – 3.0)	96.3				
E3 (3.0 – 10.0)	98.7				
MERV rating from vendor	13				
MERV rating from testing	14				

Table E-18. Initial Measured Collection Efficiency and Pressure Drop of a Commercial 24" x 24"x 12" Pleated Non-Electrostatic Filter (C14PCS)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	85.4	984	246	0.24	0.25 @ 250 fpm
0.034	83.6	1,476	369	0.41	0.40 @ 375 fpm
0.039	80.3	1,968	492	0.60	0.60 @ 500 fpm
0.045	77.1	2,460	615	0.83	0.78 @ 625 fpm
0.052	73.7				
0.060	71.5				
0.070	67.5				
0.081	65.3				
0.093	63.6				
0.11	61.1				
0.12	60.6				
0.14	61.7				
0.17	61.6				
0.19	60.0				
0.22	63.8				
0.26	64.3				
0.29	66.6				
0.30 – 0.40	62.0				
0.40 – 0.55	68.6				
0.55 – 0.70	74.4				
0.70 – 1.00	80.2				
1.00 – 1.30	84.0				
1.30 – 1.60	86.7				
1.60 – 2.20	91.3				
2.20 – 3.00	95.7				
3.00 – 4.00	97.6				
4.00 – 5.50	98.6				
5.50 – 7.00	99.1				
7.00 – 10.00	99.3				
E1 (0.30 – 1.0)	71.3				
E2 (1.0 – 3.0)	89.4				
E3 (3.0 – 10.0)	98.6				
MERV rating from vendor	14				
MERV rating from testing	12				

Table E-19. Initial Measured Collection Efficiency and Pressure Drop of a Commercial 24" x 24" x 15" 8-Pocket Electrostatic Bag Filter (C10CFS-14)

Particle Size Range or Midpoint of Range (μm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data for a 12 pocket filter (in. w.g.)
0.029	73.0	984	246	0.25	0.21 @ 250 fpm
0.034	71.8	1,476	369	0.40	0.35 @ 375 fpm
0.039	71.6	1,968	492	0.57	0.50 @ 500 fpm
0.045	69.9	2,460	615	0.74	NA
0.052	69.9				
0.060	68.8				
0.070	69.2				
0.081	66.8				
0.093	66.9				
0.11	65.0				
0.12	63.8				
0.14	62.9				
0.17	62.0				
0.19	62.5				
0.22	63.5				
0.26	64.9				
0.29	65.4				
0.30 – 0.40	72.2				
0.40 – 0.55	79.3				
0.55 – 0.70	83.3				
0.70 – 1.00	89.1				
1.00 – 1.30	92.1				
1.30 – 1.60	93.9				
1.60 – 2.20	96.1				
2.20 – 3.00	98.1				
3.00 – 4.00	98.7				
4.00 – 5.50	98.9				
5.50 – 7.00	99.0				
7.00 – 10.00	99.1				
E1 (0.30 – 1.0)	81.0				
E2 (1.0 – 3.0)	95.0				
E3 (3.0 – 10.0)	98.9				
MERV rating from vendor	14				
MERV rating from testing	14				

Table E-20. Initial Measured Collection Efficiency and Pressure Drop of a Commercial 24" x 24" x 12" Pleated Non-Electrostatic Filter (C11GM-16)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	99.9	984	246	0.37	0.42 @ 250 fpm
0.034	99.8	1,476	369	0.59	0.55 @ 375 fpm
0.039	99.7	1,968	492	0.85	0.61 @ 500 fpm
0.045	99.4	2,460	615	1.14	NA
0.052	99.0				
0.060	98.4				
0.070	97.7				
0.081	96.9				
0.093	96.2				
0.11	95.6				
0.12	95.0				
0.14	94.9				
0.17	94.9				
0.19	95.2				
0.22	94.9				
0.26	95.1				
0.29	96.3				
0.30 – 0.40	97.0				
0.40 – 0.55	98.4				
0.55 – 0.70	99.2				
0.70 – 1.00	99.6				
1.00 – 1.30	99.8				
1.30 – 1.60	99.9				
1.60 – 2.20	99.9				
2.20 – 3.00	100.0				
3.00 – 4.00	100.0				
4.00 – 5.50	100.0				
5.50 – 7.00	100.0				
7.00 – 10.00	100.0				
E1 (0.30 – 1.0)	98.6				
E2 (1.0 – 3.0)	99.9				
E3 (3.0 – 10.0)	100				
MERV rating from vendor	16				
MERV rating from testing	16				

Table E-21. Initial Measured Collection Efficiency and Pressure Drop of a Commercial 24" x 24" x 12" Pleated Non-Electrostatic Filter (C12AB-16)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	99.0	984	246	0.44	0.40 @ 250 fpm
0.034	98.9	1,476	369	0.71	NA
0.039	98.4	1,968	492	1.01	0.95 @ 500 fpm
0.045	97.7	2,460	615	1.35	NA
0.052	96.8				
0.060	96.1				
0.070	94.8				
0.081	93.9				
0.093	93.3				
0.11	92.8				
0.12	92.4				
0.14	92.5				
0.17	92.5				
0.19	93.0				
0.22	94.0				
0.26	93.8				
0.29	94.6				
0.30 – 0.40	96.1				
0.40 – 0.55	97.7				
0.55 – 0.70	98.7				
0.70 – 1.00	99.3				
1.00 – 1.30	99.4				
1.30 – 1.60	99.6				
1.60 – 2.20	99.8				
2.20 – 3.00	99.8				
3.00 – 4.00	99.8				
4.00 – 5.50	100.0				
5.50 – 7.00	100.0				
7.00 – 10.00	100.0				
E1 (0.30 – 1.0)	98.0				
E2 (1.0 – 3.0)	99.7				
E3 (3.0 – 10.0)	99.9				
MERV rating from vendor	16				
MERV rating from testing	16				

Table E-22. Initial Measured Collection Efficiency and Pressure Drop of a Commercial 24" x 24" x 12" Pleated Non-Electrostatic Filter (C13AMG-16)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	97.1	984	246	0.55	0.40 @ 238 fpm
0.034	97.3	1,476	369	0.90	0.65 @ 325 fpm
0.039	97.2	1,968	492	1.29	0.95 @ 475 fpm
0.045	97.1	2,460	615	1.71	1.35 @ 605 fpm
0.052	96.9				
0.060	96.5				
0.070	96.4				
0.081	96.2				
0.093	96.0				
0.11	96.0				
0.12	96.0				
0.14	96.1				
0.17	96.3				
0.19	96.5				
0.22	96.8				
0.26	96.5				
0.29	96.8				
0.30 – 0.40	95.5				
0.40 – 0.55	96.6				
0.55 – 0.70	96.4				
0.70 – 1.00	96.9				
1.00 – 1.30	97.0				
1.30 – 1.60	96.5				
1.60 – 2.20	96.3				
2.20 – 3.00	97.2				
3.00 – 4.00	97.0				
4.00 – 5.50	97.2				
5.50 – 7.00	97.9				
7.00 – 10.00	98.0				
E1 (0.30 – 1.0)	96.4				
E2 (1.0 – 3.0)	96.8				
E3 (3.0 – 10.0)	97.5				
MERV rating from vendor	16				
MERV rating from testing	16				

Table E-23. Initial Measured Collection Efficiency and Pressure Drop of a Commercial 24" x 24" x 12" Pleated Non-Electrostatic HEPA Filter (C114FA-H)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	99.3	984	246	0.62	NA
0.034	99.3	1,476	369	0.97	0.90 @ 344 fpm
0.039	99.3	1,968	492	1.34	1.45 @ 500 fpm
0.045	99.3	2,460	615	1.74	1.90 @ 640 fpm
0.052	99.3				
0.060	99.4				
0.070	99.4				
0.081	99.4				
0.093	99.3				
0.11	99.3				
0.12	99.3				
0.14	99.4				
0.17	99.4				
0.19	99.4				
0.22	99.4				
0.26	99.5				
0.29	99.5				
0.30 – 0.40	100.0				
0.40 – 0.55	100.0				
0.55 – 0.70	100.0				
0.70 – 1.00	100.0				
1.00 – 1.30	100.0				
1.30 – 1.60	100.0				
1.60 – 2.20	100.0				
2.20 – 3.00	100.0				
3.00 – 4.00	100.0				
4.00 – 5.50	100.0				
5.50 – 7.00	100.0				
7.00 – 10.00	100.0				
E1 (0.30 – 1.0)	100				
E2 (1.0 – 3.0)	100				
E3 (3.0 – 10.0)	100				
MERV rating from vendor	16+				
MERV rating from testing	16+				

Table E-24. Initial Measured Collection Efficiency and Pressure Drop of a Commercial 24" x 24" x 2" Pleated Electrostatic Filter (C15AAA-11)

Particle Size Range or Midpoint of Range (μm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	45.1	984	246	0.13	0.12 @ 250 fpm
0.034	50.7	1,476	369	0.22	0.23 @ 375 fpm
0.039	48.1	1,968	492	0.34	0.38 @ 500 fpm
0.045	44.1	2,460	615	0.47	0.51 @ 625 fpm
0.052	42.1				
0.060	39.5				
0.070	34.4				
0.081	32.1				
0.093	29.3				
0.11	29.1				
0.12	26.1				
0.14	25.1				
0.17	21.8				
0.19	22.9				
0.22	22.2				
0.26	16.1				
0.29	17.3				
0.30 – 0.40	29.0				
0.40 – 0.55	35.6				
0.55 – 0.70	47.1				
0.70 – 1.00	52.6				
1.00 – 1.30	66.4				
1.30 – 1.60	71.4				
1.60 – 2.20	76.5				
2.20 – 3.00	73.4				
3.00 – 4.00	71.3				
4.00 – 5.50	70.9				
5.50 – 7.00	65.4				
7.00 – 10.00	58.9				
E1 (0.30 – 1.0)	41.1				
E2 (1.0 – 3.0)	71.9				
E3 (3.0 – 10.0)	66.6				
MERV rating from vendor	11				
MERV rating from testing	7				

Table E-25. Initial Measured Collection Efficiency and Pressure Drop of a Commercial 12" x 24" x 2" Pleated Electrostatic Filter (C15AAA-11)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	36.2	492	246	0.14	0.12 @ 250 fpm
0.034	35.2	738	369	0.25	0.23 @ 375 fpm
0.039	35.4	984	492	0.40	0.38 @ 500 fpm
0.045	36.3	1,230	615	0.59	0.51 @ 625 fpm
0.052	32.9				
0.060	30.7				
0.070	31.0				
0.081	29.7				
0.093	27.0				
0.11	26.2				
0.12	25.1				
0.14	23.9				
0.17	20.8				
0.19	22.1				
0.22	22.4				
0.26	22.4				
0.29	20.9				
0.30 – 0.40	39.6				
0.40 – 0.55	40.5				
0.55 – 0.70	50.6				
0.70 – 1.00	59.1				
1.00 – 1.30	67.6				
1.30 – 1.60	73.0				
1.60 – 2.20	75.2				
2.20 – 3.00	75.9				
3.00 – 4.00	74.7				
4.00 – 5.50	71.5				
5.50 – 7.00	73.0				
7.00 – 10.00	66.5				
E1 (0.30 – 1.0)	47.5				
E2 (1.0 – 3.0)	72.9				
E3 (3.0 – 10.0)	71.4				
MERV rating from vendor	11				
MERV rating from testing	8				

Table E-26. Initial Measured Collection Efficiency and Pressure Drop of a Commercial 24" x 24" x 2" Pleated Electrostatic Filter (C17FPP-8)

Particle Size Range or Midpoint of Range (μm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	29.7	984	246	0.17	0.10 @ 250 fpm
0.034	34.8	1,476	369	0.29	0.18 @ 375 fpm
0.039	30.1	1,968	492	0.44	0.30 @ 500 fpm
0.045	28.0	2,460	615	0.63	0.45 @ 625 fpm
0.052	22.0				
0.060	20.9				
0.070	17.5				
0.081	18.4				
0.093	14.4				
0.11	12.7				
0.12	11.9				
0.14	15.3				
0.17	12.0				
0.19	13.5				
0.22	8.1				
0.26	15.0				
0.29	16.4				
0.30 – 0.40	34.5				
0.40 – 0.55	39.9				
0.55 – 0.70	52.3				
0.70 – 1.00	66.7				
1.00 – 1.30	86.7				
1.30 – 1.60	90.6				
1.60 – 2.20	93.3				
2.20 – 3.00	93.8				
3.00 – 4.00	92.2				
4.00 – 5.50	89.0				
5.50 – 7.00	62.7				
7.00 – 10.00	NA	<500 particles			
E1 (0.30 – 1.0)	48.3				
E2 (1.0 – 3.0)	91.1				
E3 (3.0 – 10.0)	81.3				
MERV rating from vendor	11				
MERV rating from testing	8				

Table E-27. Initial Measured Collection Efficiency and Pressure Drop of a Commercial 12" x 24" x 2" Pleated Electrostatic Filter (C17FPP-8)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	40.8	492	246	0.20	0.10 @ 250 fpm
0.034	36.7	738	369	0.35	0.18 @ 375 fpm
0.039	33.6	984	492	0.55	0.30 @ 500 fpm
0.045	30.4	1,230	615	0.75	0.45 @ 625 fpm
0.052	26.2				
0.060	22.1				
0.070	20.8				
0.081	18.3				
0.093	17.1				
0.11	17.9				
0.12	15.9				
0.14	14.2				
0.17	11.5				
0.19	13.9				
0.22	16.8				
0.26	17.3				
0.29	15.5				
0.30 – 0.40	30.2				
0.40 – 0.55	29.6				
0.55 – 0.70	41.4				
0.70 – 1.00	55.0				
1.00 – 1.30	69.4				
1.30 – 1.60	76.0				
1.60 – 2.20	79.2				
2.20 – 3.00	77.4				
3.00 – 4.00	73.2				
4.00 – 5.50	66.2				
5.50 – 7.00	63.8				
7.00 – 10.00	55.7				
E1 (0.30 – 1.0)	39.1				
E2 (1.0 – 3.0)	75.5				
E3 (3.0 – 10.0)	64.7				
MERV rating from vendor	11				
MERV rating from testing	7				

Table E-28. Initial Measured Collection Efficiency and Pressure Drop of a Residential 16" x 25" Electronic Air Cleaner (Unit A – used for ambient aging)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	93.1	410	148	0.05	NA
0.034	92.5	614	221	0.08	NA
0.039	92.3	819	295	0.12	0.10 @ 360 fpm
0.045	91.6	1,024	369	0.17	0.14 @ 432 fpm
0.052	91.0				0.17 @ 504 fpm
0.060	90.5				0.29 @ 720 fpm
0.070	89.7				
0.081	89.0				
0.093	88.3				
0.11	88.1				
0.12	87.3				
0.14	86.8				
0.17	85.6				
0.19	85.0				
0.22	84.2				
0.26	84.7				
0.29	83.5				
0.30 – 0.40	80.8				
0.40 – 0.55	82.8				
0.55 – 0.70	85.4				
0.70 – 1.00	87.7				
1.00 – 1.30	90.6				
1.30 – 1.60	91.9				
1.60 – 2.20	94.1				
2.20 – 3.00	95.6				
3.00 – 4.00	96.7				
4.00 – 5.50	97.8				
5.50 – 7.00	98.0				
7.00 – 10.00	99.2				
E1 (0.30 – 1.0)	84.2				
E2 (1.0 – 3.0)	93.1				
E3 (3.0 – 10.0)	97.9				
MERV rating from vendor	15				
MERV rating from testing	14				

Table E-29. Initial Measured Collection Efficiency and Pressure Drop of a Residential 16" x 25" Electronic Air Cleaner (Unit A – used for silicon vapor tests)

Particle Size Range or Midpoint of Range (μm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	95.1	410	148	0.05	NA
0.034	95.1	614	221	0.07	NA
0.039	95.4	819	295	0.11	0.10 @ 360 fpm
0.045	95.2	1,024	369	0.15	0.14 @ 432 fpm
0.052	94.9				0.17 @ 504 fpm
0.060	94.6				0.29 @ 720 fpm
0.070	94.6				
0.081	94.2				
0.093	94.3				
0.11	94.2				
0.12	93.9				
0.14	93.7				
0.17	93.3				
0.19	93.1				
0.22	92.8				
0.26	93.7				
0.29	93.3				
0.30 – 0.40	89.3				
0.40 – 0.55	90.3				
0.55 – 0.70	91.4				
0.70 – 1.00	92.2				
1.00 – 1.30	93.4				
1.30 – 1.60	94.0				
1.60 – 2.20	94.8				
2.20 – 3.00	95.4				
3.00 – 4.00	96.1				
4.00 – 5.50	96.9				
5.50 – 7.00	97.0				
7.00 – 10.00	96.3				
E1 (0.30 – 1.0)	90.8				
E2 (1.0 – 3.0)	94.4				
E3 (3.0 – 10.0)	96.6				
MERV rating from vendor	15				
MERV rating from testing	15				

Table E-30. Initial Measured Collection Efficiency and Pressure Drop of a Residential 20" x 20" Electronic Air Cleaner (Unit H – used for ambient aging)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	93.8	410	148	0.03	0.03 @ 148 fpm
0.034	94.5	614	221	0.06	0.04 @ 221 fpm
0.039	94.8	819	295	0.11	0.06 @ 295 fpm
0.045	94.4	1,024	369	0.17	0.09 @ 369 fpm
0.052	93.6				
0.060	92.8				
0.070	91.9				
0.081	91.4				
0.093	90.2				
0.11	89.4				
0.12	88.8				
0.14	88.5				
0.17	87.2				
0.19	88.5				
0.22	87.8				
0.26	87.5				
0.29	87.1				
0.30 – 0.40	89.3				
0.40 – 0.55	91.9				
0.55 – 0.70	94.0				
0.70 – 1.00	95.5				
1.00 – 1.30	96.5				
1.30 – 1.60	96.6				
1.60 – 2.20	97.1				
2.20 – 3.00	97.4				
3.00 – 4.00	97.6				
4.00 – 5.50	98.0				
5.50 – 7.00	98.0				
7.00 – 10.00	98.8				
E1 (0.30 – 1.0)	92.7				
E2 (1.0 – 3.0)	96.9				
E3 (3.0 – 10.0)	98.1				
MERV rating from vendor	Up to 12				
MERV rating from testing	15				

Table E-31. Initial Measured Collection Efficiency and Pressure Drop of a Residential 20" x 20" Electronic Air Cleaner (Unit H – used for silicon vapor tests)

Particle Size Range or Midpoint of Range (μm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	92.2	410	148	0.03	0.03 @ 148 fpm
0.034	94.0	614	221	0.06	0.04 @ 221 fpm
0.039	94.2	819	295	0.11	0.06 @ 295 fpm
0.045	93.8	1,024	369	0.17	0.09 @ 369 fpm
0.052	93.4				
0.060	92.5				
0.070	91.5				
0.081	90.5				
0.093	89.4				
0.11	88.3				
0.12	87.7				
0.14	86.6				
0.17	86.9				
0.19	87.0				
0.22	87.1				
0.26	87.3				
0.29	87.9				
0.30 – 0.40	86.8				
0.40 – 0.55	90.5				
0.55 – 0.70	93.3				
0.70 – 1.00	95.2				
1.00 – 1.30	96.5				
1.30 – 1.60	97.1				
1.60 – 2.20	97.4				
2.20 – 3.00	97.7				
3.00 – 4.00	98.3				
4.00 – 5.50	98.5				
5.50 – 7.00	98.9				
7.00 – 10.00	99.5				
E1 (0.30 – 1.0)	91.5				
E2 (1.0 – 3.0)	97.2				
E3 (3.0 – 10.0)	98.8				
MERV rating from vendor	Up to 12				
MERV rating from testing	15				

Table E-32. Initial Measured Collection Efficiency and Pressure Drop of a Residential 20" x 20" Electronic Air Cleaner (Unit P – used for ambient aging)

Particle Size Range or Midpoint of Range (μm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	81.2	410	148	0.02	NA
0.034	84.4	614	221	0.04	NA
0.039	88.2	819	295	0.06	NA
0.045	88.5	1,024	369	0.09	0.11 @ 504 fpm
0.052	87.9				
0.060	86.7				
0.070	85.5				
0.081	83.7				
0.093	81.7				
0.11	80.9				
0.12	80.1				
0.14	78.5				
0.17	79.0				
0.19	77.5				
0.22	80.0				
0.26	79.7				
0.29	80.8				
0.30 – 0.40	76.7				
0.40 – 0.55	82.1				
0.55 – 0.70	86.5				
0.70 – 1.00	90.5				
1.00 – 1.30	93.6				
1.30 – 1.60	94.9				
1.60 – 2.20	95.7				
2.20 – 3.00	96.2				
3.00 – 4.00	96.6				
4.00 – 5.50	97.0				
5.50 – 7.00	97.6				
7.00 – 10.00	97.1				
E1 (0.30 – 1.0)	84.0				
E2 (1.0 – 3.0)	95.1				
E3 (3.0 – 10.0)	97.1				
MERV rating from vendor	NA				
MERV rating from testing	14				

Table E-33. Initial Measured Collection Efficiency and Pressure Drop of a Residential 20" x 20" Electronic Air Cleaner (Unit P – used for silicon vapor tests)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)	Air Flow Rate (cfm)	Air Velocity (fpm)	Measured Pressure Drop (in. w.g.)	Manufacturer's Pressure Drop Data (in. w.g.)
0.029	86.4	410	148	0.03	NA
0.034	88.2	614	221	0.05	NA
0.039	89.1	819	295	0.08	NA
0.045	88.8	1,024	369	0.13	0.11 @ 504 fpm
0.052	87.3				
0.060	86.1				
0.070	84.1				
0.081	83.1				
0.093	80.6				
0.11	80.0				
0.12	78.4				
0.14	76.9				
0.17	74.5				
0.19	74.3				
0.22	73.9				
0.26	72.9				
0.29	72.5				
0.30 – 0.40	73.9				
0.40 – 0.55	80.3				
0.55 – 0.70	85.7				
0.70 – 1.00	90.0				
1.00 – 1.30	93.7				
1.30 – 1.60	95.0				
1.60 – 2.20	96.0				
2.20 – 3.00	96.8				
3.00 – 4.00	96.9				
4.00 – 5.50	97.4				
5.50 – 7.00	97.0				
7.00 – 10.00	96.4				
E1 (0.30 – 1.0)	82.5				
E2 (1.0 – 3.0)	95.3				
E3 (3.0 – 10.0)	96.9				
MERV rating from vendor	NA				
MERV rating from testing	14				

Appendix F

Results From the Bioaerosol Evaluations of "Off-The-Shelf" Air Cleaners

Table F-1. Results from Bioaerosol Evaluation of Residential Filter 2NS-8-1

Sample	Air Flow Velocity (fpm)	Average Air Flow Velocity (fpm)	Air Flow Velocity Standard Deviation (fpm)	Air Flow Velocity Coefficient of Variance (%)	CFU/liter of air	Average Concentration (CFU/liter of air)	Std. Dev.	Coefficient of Variance
Upstream	203	208 (832 cfm)	37.6	18.1	$4.99*10^3$	$4.87*10^3$	$6.97*10^2$	14%
Upstream	253				$3.52*10^3$			
Upstream	189				$4.30*10^3$			
Upstream	221				$6.00*10^3$			
Upstream	267				$5.27*10^3$			
Upstream	224				$5.28*10^3$			
Upstream	175				$5.07*10^3$			
Upstream	206				$4.82*10^3$			
Upstream	135				$4.56*10^3$			
Downstream	-	-	-	-	$3.66*10^3$	$4.15*10^3$	$6.50*10^2$	16%
Downstream	-	-	-	-	$4.14*10^3$			
Downstream	-	-	-	-	$4.37*10^3$			
Downstream	-	-	-	-	$3.34*10^3$			
Downstream	-	-	-	-	$3.96*10^3$			
Downstream	-	-	-	-	$5.06*10^3$			
Downstream	-	-	-	-	$4.91*10^3$			
Downstream	-	-	-	-	$3.28*10^3$			
Downstream	-	-	-	-	$4.63*10^3$			
Background	-	-	-	-	<2.7			
Background	-	-	-	-	<2.8			
Pressure Drop (in. w.g.)	0.20							
$P_{measured}$						0.853		
P_{100}						0.995		
$P_{corrected}$						0.857		
Filtration Efficiency						14%		
Combined Standard Deviation						18%		

Table F-2. Results from Bioaerosol Evaluation of Residential Filter 4FUA-12-1

Sample	Air Flow Velocity (fpm)	Average Air Flow Velocity (fpm)	Air Flow Velocity Standard Deviation (fpm)	Air Flow Velocity Coefficient of Variance (%)	CFU/liter of air	Average Concentration (CFU/liter of air)	Std. Dev.	Coefficient of Variance
Upstream	220	207 (828 cfm)	43.2	20.8	$5.93*10^3$	$5.28*10^3$	$5.05*10^2$	10%
Upstream	274				$5.25*10^3$			
Upstream	188				$4.22*10^3$			
Upstream	197				$5.58*10^3$			
Upstream	262				$3.89*10^{2A}$			
Upstream	210				$5.48*10^3$			
Upstream	165				$5.47*10^3$			
Upstream	224				$5.29*10^3$			
Upstream	126				$5.03*10^3$			
Downstream	-	-	-	-	$3.06*10^3$	$2.61*10^3$	$7.15*10^2$	27%
Downstream	-	-	-	-	$2.90*10^3$			
Downstream	-	-	-	-	$2.99*10^3$			
Downstream	-	-	-	-	$3.47*10^3$			
Downstream	-	-	-	-	$1.63*10^3$			
Downstream	-	-	-	-	$2.24*10^{2A}$			
Downstream	-	-	-	-	$2.32*10^3$			
Downstream	-	-	-	-	$2.97*10^3$			
Downstream	-	-	-	-	$1.50*10^3$			
Background	-	-	-	-	<2.7			
Background	-	-	-	-	<2.8			
Pressure Drop (in. w.g.)	0.15							
$P_{measured}$						0.493		
P_{100}						0.995		
$P_{corrected}$						0.496		
Filtration Efficiency						50%		
Combined Standard Deviation						14%		

[A] – Excluded from calculations due to difference of an order of magnitude from the average.

Table F-3. Results from Bioaerosol Evaluation of Residential Filter 8NM-10-1

Sample	Air Flow Velocity (fpm)	Average Air Flow Velocity (fpm)	Air Flow Velocity Standard Deviation (fpm)	Air Flow Velocity Coefficient of Variance (%)	CFU/liter of air	Average Concentration (CFU/liter of air)	Std. Dev.	Coefficient of Variance
Upstream	165	209 (836 cfm)	53.2	25.4	$5.38*10^3$	$4.91*10^3$	$4.40*10^2$	9%
Upstream	280				$4.59*10^3$			
Upstream	186				$5.75*10^3$			
Upstream	153				$5.01*10^3$			
Upstream	299				$4.61*10^3$			
Upstream	225				$4.78*10^3$			
Upstream	167				$4.83*10^3$			
Upstream	252				$4.28*10^3$			
Upstream	156				$4.92*10^3$			
Downstream	-	-	-	-	$2.97*10^3$	$2.93*10^3$	$1.68*10^2$	6%
Downstream	-	-	-	-	$2.88*10^3$			
Downstream	-	-	-	-	$2.82*10^3$			
Downstream	-	-	-	-	$2.62*10^3$			
Downstream	-	-	-	-	$2.92*10^3$			
Downstream	-	-	-	-	$2.93*10^3$			
Downstream	-	-	-	-	$2.90*10^3$			
Downstream	-	-	-	-	$3.21*10^3$			
Downstream	-	-	-	-	$3.12*10^3$			
Background	-	-	-	-	<2.7			
Background	-	-	-	-	<2.8			
Pressure Drop (in. w.g.)	0.15							
$P_{measured}$						0.597		
P_{100}						0.995		
$P_{corrected}$						0.600		
Filtration Efficiency						40%		
Combined Standard Deviation						6%		

Table F-4. Results from Bioaerosol Evaluation of Residential Filter 6DDUE-8-12

Sample	Air Flow Velocity (fpm)	Average Air Flow Velocity (fpm)	Air Flow Velocity Standard Deviation (fpm)	Air Flow Velocity Coefficient of Variance (%)	CFU/liter of air	Average Concentration (CFU/liter of air)	Std. Dev.	Coefficient of Variance
Upstream	184	211 (844 cfm)	44.2	21.0	$5.41*10^3$	$4.45*10^3$	$5.98*10^2$	13%
Upstream	257				$4.58*10^3$			
Upstream	191				$4.31*10^3$			
Upstream	231				$5.42*10^3$			
Upstream	288				$4.12*10^3$			
Upstream	203				$4.42*10^3$			
Upstream	178				$3.82*10^3$			
Upstream	232				$4.09*10^3$			
Upstream	131				$3.86*10^3$			
Downstream	-	-	-	-	$4.46*10^3$	$4.15*10^3$	$6.48*10^2$	16%
Downstream	-	-	-	-	$4.09*10^3$			
Downstream	-	-	-	-	$3.20*10^3$			
Downstream	-	-	-	-	$5.34*10^3$			
Downstream	-	-	-	-	$4.75*10^3$			
Downstream	-	-	-	-	$3.46*10^3$			
Downstream	-	-	-	-	$4.07*10^3$			
Downstream	-	-	-	-	$3.85*10^3$			
Downstream	-	-	-	-	$4.11*10^3$			
Background	-	-	-	-	<2.7			
Background	-	-	-	-	<2.8			
Pressure Drop (in. w.g.)	0.13							
$P_{measured}$						0.932		
P_{100}						0.995		
$P_{corrected}$						0.937		
Filtration Efficiency						6%		
Combined Standard Deviation						19%		

Table F-5. Results from Bioaerosol Evaluation of Electronic Air Cleaner Unit A

Sample	Air Flow Velocity (fpm)	Average Air Flow Velocity (fpm)	Air Flow Velocity Standard Deviation (fpm)	Air Flow Velocity Coefficient of Variance (%)	CFU/liter of air	Average Concentration (CFU/liter of air)	Std. Dev.	Coefficient of Variance
Upstream	173	200 (800 cfm)	35.6	17.8	$7.21*10^3$	$4.56*10^3$	$1.26*10^3$	28%
Upstream	247				$4.16*10^3$			
Upstream	177				$3.51*10^3$			
Upstream	173				$4.78*10^3$			
Upstream	266				$4.55*10^3$			
Upstream	206				$3.60*10^3$			
Upstream	167				$5.77*10^3$			
Upstream	222				$4.31*10^3$			
Upstream	165				$3.17*10^3$			
Downstream	-	-	-	-	$1.94*10^2$	$3.19*10^2$	$3.66*10^2$	115%
Downstream	-	-	-	-	$2.42*10^1$			
Downstream	-	-	-	-	$5.40*10^0$			
Downstream	-	-	-	-	$1.07*10^3$			
Downstream	-	-	-	-	$7.36*10^2$			
Downstream	-	-	-	-	$3.88*10^2$			
Downstream	-	-	-	-	$3.19*10^2$			
Downstream	-	-	-	-	$4.34*10^1$			
Downstream	-	-	-	-	$8.69*10^1$			
Background	-	-	-	-	<2.7			
Background	-	-	-	-	<2.8			
Pressure Drop (in. w.g.)	0.06							
$P_{measured}$						0.069		
P_{100}						0.995		
$P_{corrected}$						0.070		
Filtration Efficiency						93%		
Combined Standard Deviation						8%		

Table F-6. Results from Bioaerosol Evaluation of Electronic Air Cleaner Unit H

Sample	Air Flow Velocity (fpm)	Average Air Flow Velocity (fpm)	Air Flow Velocity Standard Deviation (fpm)	Air Flow Velocity Coefficient of Variance (%)	CFU/liter of air	Average Concentration (CFU/liter of air)	Std. Dev.	Coefficient of Variance
Upstream	209	210 (840 cfm)	44.7	21.2	$5.74*10^3$	$4.10*10^3$	$8.74*10^2$	21%
Upstream	275				$4.44*10^3$			
Upstream	223				$3.75*10^3$			
Upstream	210				$4.80*10^3$			
Upstream	274				$3.87*10^3$			
Upstream	208				$3.72*10^3$			
Upstream	158				$2.58*10^3$			
Upstream	206				$4.28*10^3$			
Upstream	128				$3.70*10^3$			
Downstream	-	-	-	-	$5.85*10^2$	$4.38*10^2$	$2.50*10^2$	57%
Downstream	-	-	-	-	$1.43*10^2$			
Downstream	-	-	-	-	$7.91*10^2$			
Downstream	-	-	-	-	$2.62*10^2$			
Downstream	-	-	-	-	$6.48*10^1$			
Downstream	-	-	-	-	$4.96*10^2$			
Downstream	-	-	-	-	$6.82*10^2$			
Downstream	-	-	-	-	$3.28*10^2$			
Downstream	-	-	-	-	$5.89*10^2$			
Background	-	-	-	-	<2.7			
Background	-	-	-	-	<2.8			
Pressure Drop (in. w.g.)	0.05							
$P_{measured}$						0.107		
P_{100}						0.995		
$P_{corrected}$						0.107		
Filtration Efficiency						89%		
Combined Standard Deviation						7%		

Table F-7. Results from Bioaerosol Evaluation of Electronic Air Cleaner Unit P

Sample	Air Flow Velocity (fpm)	Average Air Flow Velocity (fpm)	Air Flow Velocity Standard Deviation (fpm)	Air Flow Velocity Coefficient of Variance (%)	CFU/liter of air	Average Concentration (CFU/liter of air)	Std. Dev.	Coefficient of Variance
Upstream	190	201 (804 cfm)	37.5	18.6	$6.22*10^3$	$4.74*10^3$	$8.53*10^2$	18%
Upstream	258				$4.49*10^3$			
Upstream	187				$3.42*10^3$			
Upstream	202				$5.78*10^3$			
Upstream	260				$4.72*10^3$			
Upstream	208				$4.57*10^3$			
Upstream	162				$5.02*10^3$			
Upstream	207				$4.45*10^3$			
Upstream	138				$4.01*10^3$			
Downstream	-	-	-	-	$4.36*10^2$	$2.58*10^2$	$1.76*10^2$	68%
Downstream	-	-	-	-	$3.58*10^1$			
Downstream	-	-	-	-	$3.15*10^2$			
Downstream	-	-	-	-	$3.87*10^2$			
Downstream	-	-	-	-	$5.33*10^1$			
Downstream	-	-	-	-	$3.65*10^2$			
Downstream	-	-	-	-	$4.82*10^2$			
Downstream	-	-	-	-	$6.47*10^1$			
Downstream	-	-	-	-	$1.85*10^2$			
Background	-	-	-	-	<2.7			
Background	-	-	-	-	<2.8			
Pressure Drop (in. w.g.)	0.03							
$P_{measured}$						0.054		
P_{100}						0.995		
$P_{corrected}$						0.054		
Filtration Efficiency						95%		
Combined Standard Deviation						4%		

Table F-8. Results from Bioaerosol Evaluation of Filter C15AAA-11-BIO (12" x 24" x 2")

Sample	Air Flow Velocity (fpm)	Average Air Flow Velocity (fpm)	Air Flow Velocity Standard Deviation (fpm)	Air Flow Velocity Coefficient of Variance (%)	CFU/liter of air	Average Concentration (CFU/liter of air)	Std. Dev.	Coefficient of Variance
Upstream	225	230 (920 cfm)	38.4	16.7	$4.94*10^3$	$4.50*10^3$	$4.79*10^2$	11%
Upstream	263				$4.19*10^3$			
Upstream	180				$4.78*10^3$			
Upstream	208				$3.85*10^3$			
Upstream	296				$3.88*10^3$			
Upstream	240				$4.23*10^3$			
Upstream	179				$4.80*10^3$			
Upstream	269				$4.69*10^3$			
Upstream	206				$5.18*10^3$			
Downstream	-	-	-	-	$1.71*10^3$	$1.75*10^3$	$6.53*10^1$	4%
Downstream	-	-	-	-	$1.87*10^3$			
Downstream	-	-	-	-	$1.69*10^3$			
Downstream	-	-	-	-	$1.67*10^3$			
Downstream	-	-	-	-	$1.74*10^3$			
Downstream	-	-	-	-	$1.79*10^3$			
Downstream	-	-	-	-	$1.80*10^3$			
Downstream	-	-	-	-	$1.71*10^3$			
Downstream	-	-	-	-	$1.80*10^3$			
Background	-	-	-	-	<2.7			
Background	-	-	-	-	<2.8			
Pressure Drop (in. w.g.)	0.35							
$P_{measured}$						0.389		
P_{100}						1.034		
$P_{corrected}$						0.376		
Filtration Efficiency						62%		
Combined Standard Deviation						4%		

Table F-9. Results from Bioaerosol Evaluation of Filter C17FPP-8-BIO (12" x 24" x 2")

Sample	Air Flow Velocity (fpm)	Average Air Flow Velocity (fpm)	Air Flow Velocity Standard Deviation (fpm)	Air Flow Velocity Coefficient of Variance (%)	CFU/liter of air	Average Concentration (CFU/liter of air)	Std. Dev.	Coefficient of Variance
Upstream	238	254 (1016 cfm)	59.9	23.5	$4.66*10^3$	$3.90*10^3$	$6.01*10^2$	15%
Upstream	356				$4.66*10^3$			
Upstream	249				$4.48*10^3$			
Upstream	237				$3.06*10^3$			
Upstream	344				$3.68*10^3$			
Upstream	214				$3.49*10^3$			
Upstream	195				$4.19*10^3$			
Upstream	287				$3.46*10^3$			
Upstream	170				$3.45*10^3$			
Downstream	-	-	-	-	$2.42*10^3$	$2.40*10^3$	$2.06*10^2$	9%
Downstream	-	-	-	-	$2.49*10^3$			
Downstream	-	-	-	-	$2.37*10^3$			
Downstream	-	-	-	-	$2.09*10^3$			
Downstream	-	-	-	-	$2.80*10^3$			
Downstream	-	-	-	-	$2.23*10^3$			
Downstream	-	-	-	-	$2.56*10^3$			
Downstream	-	-	-	-	$2.33*10^3$			
Downstream	-	-	-	-	$2.28*10^3$			
Background	-	-	-	-	<2.7			
Background	-	-	-	-	<2.8			
Pressure Drop (in. w.g.)	0.45							
$P_{measured}$						0.614		
P_{100}						1.034		
$P_{corrected}$						0.594		
Filtration Efficiency						41%		
Combined Standard Deviation						11%		

Table F-10. Results from Bioaerosol Evaluation of Filter C11GM-16-BIO (12" x 24" x 12")

Sample	Air Flow Velocity (fpm)	Average Air Flow Velocity (fpm)	Air Flow Velocity Standard Deviation (fpm)	Air Flow Velocity Coefficient of Variance (%)	CFU/liter of air	Average Concentration (CFU/liter of air)	Std. Dev.	Coefficient of Variance
Upstream	258	251 (1004 cfm)	49.0	19.5	$3.95*10^3$	$4.45*10^3$	$5.74*10^2$	13%
Upstream	327				$5.05*10^3$			
Upstream	253				$5.02*10^3$			
Upstream	272				$3.67*10^3$			
Upstream	313				$4.36*10^3$			
Upstream	214				$4.82*10^3$			
Upstream	169				$3.68*10^3$			
Upstream	257				$4.44*10^3$			
Upstream	193				$5.04*10^3$			
Downstream	-	-	-	-	$1.02*10^1$	$9.47*10^0$	$4.92*10^0$	52%
Downstream	-	-	-	-	$2.63*10^0$			
Downstream	-	-	-	-	$1.53*10^1$			
Downstream	-	-	-	-	$1.26*10^1$			
Downstream	-	-	-	-	$1.42*10^1$			
Downstream	-	-	-	-	$1.37*10^1$			
Downstream	-	-	-	-	$5.46*10^0$			
Downstream	-	-	-	-	$2.77*10^0$			
Downstream	-	-	-	-	$8.33*10^0$			
Background	-	-	-	-	<2.7			
Background	-	-	-	-	<2.8			
Pressure Drop (in. w.g.)	0.65							
$P_{measured}$						0.002		
P_{100}						1.034		
$P_{corrected}$						0.002		
Filtration Efficiency						99.8%		
Combined Standard Deviation						0.1%		

Appendix G
Results From the Inert Aerosol Evaluations of the Aged Air Cleaners

Table G-1. Measured Collection Efficiencies During Aging of a Residential 16" x 25" x 1" Pleated Electrostatic Filter (6DDUE-8)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)				
	0 weeks	2 weeks	4 weeks	8 weeks	12 weeks
0.029	25.0	16.8	6.8	13.9	27.9
0.034	33.8	16.6	3.6	16.5	24.5
0.039	30.8	15.7	0.5	2.9	21.3
0.045	28.0	12.8	0.0	2.8	23.1
0.052	27.1	11.2	0.0	1.4	19.9
0.060	25.7	10.5	0.0	0.0	20.3
0.070	23.0	7.7	0.0	1.4	19.9
0.081	22.3	7.3	0.0	0.1	20.5
0.093	22.3	6.6	0.0	0.0	20.6
0.11	23.6	8.8	0.0	0.0	22.1
0.12	23.3	7.3	0.0	0.0	21.7
0.14	23.2	6.4	0.0	0.0	22.0
0.17	21.8	5.2	0.0	0.0	22.9
0.19	25.4	5.6	0.0	0.0	24.0
0.22	25.3	3.8	0.0	0.0	22.5
0.26	18.2	2.5	0.0	7.5	24.7
0.29	18.1	3.8	0.0	8.2	29.1
0.30 – 0.40	16.1	4.7	8.4	0.0	2.3
0.40 – 0.55	14.0	7.1	11.1	1.9	5.7
0.55 – 0.70	21.4	7.5	12.6	5.3	11.8
0.70 – 1.00	31.1	9.8	16.3	10.6	24.0
1.00 – 1.30	44.8	15.2	22.9	19.3	43.2
1.30 – 1.60	50.6	17.4	27.6	27.7	57.2
1.60 – 2.20	55.6	26.1	39.8	40.7	72.7
2.20 – 3.00	56.8	44.6	62.8	54.6	84.9
3.00 – 4.00	57.6	59.5	75.6	64.9	90.4
4.00 – 5.50	55.5	72.7	86.6	69.5	93.6
5.50 – 7.00	59.2	82.6	93.2	69.9	94.6
7.00 – 10.00	54.9	86.2	95.1	64.4	94.3
E1 (0.30 – 1.0)	20.6	7.3	12.1	4.5	11.0
E2 (1.0 – 3.0)	51.9	25.8	38.3	35.6	64.5
E3 (3.0 – 10.0)	56.8	75.3	87.6	67.2	93.2
MERV rating from vendor	8	8	8	8	8
MERV rating from testing	7	8	9	7	10

Table G-2. Measured Pressure Drops During Aging of a Residential 16" x 25" x 1" Pleated Electrostatic Filter (6DDUE-8)

Weeks of Use (hours of operation)	Mass Gained (g)	Measured Pressure Drop (in. w.g.)			
		410 cfm (148 fpm)	614 cfm (221 fpm)	819 cfm (295 fpm)	1,024 cfm (369 fpm)
0 (0)	0	0.06	0.1	0.14	0.19
2 (199)	1	0.07	0.11	0.16	0.23
4 (544)	8	0.10	0.16	0.23	0.31
8 (1,040)	7	0.09	0.13	0.19	0.26
12 (1,307)	5	0.11	0.17	0.26	0.34
Manufacturer's Pressure Drop Data (in. w.g.)		0.07 @ 148 fpm	0.12 @ 221 fpm	0.17 @ 295 fpm	0.23 @ 369 fpm

Table G-3. Measured Collection Efficiencies During Aging of a Residential 16" x 25" x 1" Pleated Electrostatic Filter (8NM-10)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)				
	0 weeks	2 weeks	4 weeks	8 weeks	12 weeks
0.029	22.7	30.0	29.9	21.0	31.0
0.034	20.2	26.0	28.7	23.7	29.0
0.039	18.5	25.0	23.2	18.6	27.8
0.045	17.9	23.3	21.5	17.6	25.6
0.052	15.5	20.0	20.1	14.3	23.6
0.060	13.8	18.3	15.9	13.6	22.6
0.070	13.1	18.1	16.8	12.8	19.9
0.081	13.1	17.5	17.0	9.2	22.0
0.093	11.8	20.1	17.2	7.8	22.4
0.11	10.8	18.3	16.0	8.3	23.9
0.12	9.4	18.7	14.9	9.2	26.1
0.14	10.6	16.8	13.9	10.4	27.9
0.17	10.0	17.6	15.2	8.7	31.0
0.19	7.9	19.6	13.8	7.9	33.9
0.22	13.6	21.0	14.2	11.0	36.2
0.26	12.6	21.8	13.6	10.6	43.6
0.29	18.0	17.2	15.8	13.7	47.2
0.30 – 0.40	16.9	6.8	16.5	3.5	48.1
0.40 – 0.55	20.5	16.4	22.8	11.8	59.5
0.55 – 0.70	33.8	21.8	29.3	20.6	72.8
0.70 – 1.00	53.7	33.1	40.4	36.3	82.1
1.00 – 1.30	72.4	42.3	51.3	53.6	88.2
1.30 – 1.60	80.4	50.3	59.1	64.0	90.3
1.60 – 2.20	86.8	63.9	71.0	76.0	92.0
2.20 – 3.00	89.8	80.8	85.0	84.1	93.1
3.00 – 4.00	91.0	87.5	90.4	89.7	93.6
4.00 – 5.50	91.5	91.7	93.6	91.9	94.1
5.50 – 7.00	91.3	94.1	95.3	92.3	93.5
7.00 – 10.00	91.8	94.9	96.0	90.8	92.5
E1 (0.30 – 1.0)	31.2	19.5	27.2	18.1	65.6
E2 (1.0 – 3.0)	82.4	59.3	66.6	69.4	90.9
E3 (3.0 – 10.0)	91.4	92.1	93.8	91.2	93.4
MERV rating from vendor	10	10	10	10	10
MERV rating from testing	12	10	11	11	13

Table G-4. Measured Pressure Drops During Aging of a Residential 16" x 25" x 1" Pleated Electrostatic Filter (8NM-10)

Weeks of Use (hours of operation)	**Mass Gained** (g)	**Measured Pressure Drop** (in. w.g.)			
		410 cfm (148 fpm)	**614 cfm** (221 fpm)	**819 cfm** (295 fpm)	**1,024 cfm** (369 fpm)
0 (0)	0	0.17	0.29	0.43	0.59
2 (250)	2	0.20	0.34	0.50	0.69
4 (450)	1	0.23	0.39	0.58	0.80
8 (892)	3	0.20	0.33	0.49	0.68
12 (1,272)	9	0.67	1.19	1.75	2.38
Manufacturer's Pressure Drop Data (in. w.g.)		NA	NA	NA	NA

Table G-5. Measured Collection Efficiencies During Aging of a Commercial 24" x 24" x 2" Pleated Electrostatic Filter (C17FPP-8)

Particle Size Range or Midpoint of Range (μm)	Particle Size Efficiency (%)					
	0 weeks (12 x 24 filter)	0 weeks	2 weeks	4 weeks	8 weeks	16 weeks
0.029	40.8	29.7	22.5	25.5	10.2	21.4
0.034	36.7	34.8	24.2	24.6	11.3	19.0
0.039	33.6	30.1	21.1	21.7	11.4	16.9
0.045	30.4	28.0	18.0	19.7	10.9	11.0
0.052	26.2	22.0	16.2	16.1	10.6	7.5
0.060	22.1	20.9	16.5	14.2	8.9	4.7
0.070	20.8	17.5	15.0	15.0	8.6	5.9
0.081	18.3	18.4	11.5	12.0	7.3	4.5
0.093	17.1	14.4	9.9	9.1	6.5	1.7
0.11	17.9	12.7	10.4	8.8	6.5	1.3
0.12	15.9	11.9	11.6	7.4	7.8	2.4
0.14	14.2	15.3	11.3	5.6	6.9	2.8
0.17	11.5	12.0	8.1	3.4	10.9	1.9
0.19	13.9	13.5	7.5	0.3	10.7	1.4
0.22	16.8	8.1	12.3	3.5	11.0	0.0
0.26	17.3	15.0	9.7	0.0	12.9	1.1
0.29	15.5	16.4	14.2	1.0	15.8	4.5
0.30 – 0.40	30.2	34.0	1.5	1.5	4.7	0.0
0.40 – 0.55	29.6	37.1	2.3	2.6	6.6	0.3
0.55 – 0.70	41.4	52.7	3.7	4.4	7.7	2.3
0.70 – 1.00	55.0	65.5	11.3	10.5	15.1	12.5
1.00 – 1.30	69.4	85.3	13.0	11.5	16.8	14.5
1.30 – 1.60	76.0	90.3	19.3	17.6	22.4	20.6
1.60 – 2.20	79.2	93.0	29.8	27.5	33.5	33.8
2.20 – 3.00	77.4	93.8	47.2	45.6	51.2	52.4
3.00 – 4.00	73.2	92.9	60.1	59.7	64.9	66.0
4.00 – 5.50	66.2	90.1	72.7	73.4	76.6	76.3
5.50 – 7.00	63.8	79.2	77.0	79.0	82.3	81.1
7.00 – 10.00	55.7	60.9	73.4	78.0	79.5	76.2
E1 (0.30 – 1.0)	39.1	48.3	4.7	4.7	8.6	3.8
E2 (1.0 – 3.0)	75.5	91.1	27.3	25.6	31.0	30.3
E3 (3.0 – 10.0)	64.7	81.3	70.8	72.5	75.8	74.9
MERV rating from vendor	8	8	8	8	8	8
MERV rating from testing	7	8	8	8	8	8

Table G-6. Measured Pressure Drops During Aging of a Commercial 24" x 24" x 2" Pleated Electrostatic Filter (C17FPP-8)

Weeks of Use (hours of operation)	**Mass Gained** (g)	**Measured Pressure Drop** (in. w.g.)			
		984 cfm (246 fpm)	**1476 cfm** (369 fpm)	**1968 cfm** (492 fpm)	**2460 cfm** (615 fpm)
0 (0) (12" x 24" filter)	0	0.20	0.35	0.55	0.75
0 (0)	0	0.17	0.29	0.44	0.63
2 (336)	8	0.17	0.30	0.45	0.64
4 (672)	20	0.17	0.30	0.45	0.64
8 (1,344)	38	0.18	0.31	0.47	0.66
16 (2,688)	82	0.22	0.37	0.57	0.79
Manufacturer's Pressure Drop Data (in. w.g.)		0.10 at 250 fpm	0.18 at 375 fpm	0.30 at 500 fpm	0.45 at 625 fpm

Table G-7. Measured Collection Efficiencies During Aging of a Commercial 24" x 24" x 2" Pleated Electrostatic Filter (C15AAA-11)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)					
	0 weeks (12 x 24 filter)	0 weeks	2 weeks	4 weeks	8 weeks	16 weeks
0.029	36.2	45.1	16.3	15.1	11.9	14.8
0.034	35.2	50.7	10.6	10.0	14.3	13.0
0.039	35.4	48.1	9.2	8.8	12.1	10.8
0.045	36.3	44.1	6.7	4.4	11.1	5.7
0.052	32.9	42.1	3.9	5.3	11.4	5.8
0.060	30.7	39.5	0.3	0.3	9.1	3.9
0.070	31.0	34.4	0.0	0.0	10.8	2.8
0.081	29.7	32.1	0.0	0.0	11.7	2.5
0.093	27.0	29.3	0.0	0.0	12.0	0.0
0.11	26.2	29.1	0.0	0.0	11.8	0.0
0.12	25.1	26.1	0.0	0.0	11.1	0.0
0.14	23.9	25.1	0.0	0.0	12.3	0.0
0.17	20.8	21.8	0.0	0.0	14.4	0.0
0.19	22.1	22.9	0.0	0.0	14.3	0.0
0.22	22.4	22.2	0.0	0.0	11.6	0.0
0.26	22.4	16.1	0.0	0.0	14.6	0.0
0.29	20.9	17.3	0.0	0.0	13.6	0.0
0.30 – 0.40	39.6	29.0	8.2	7.1	0.9	2.9
0.40 – 0.55	40.5	35.6	8.8	8.0	0.8	4.5
0.55 – 0.70	50.6	47.1	11.6	11.3	2.1	5.2
0.70 – 1.00	59.1	52.6	15.4	14.8	9.4	12.7
1.00 – 1.30	67.6	66.4	16.5	14.2	10.4	13.2
1.30 – 1.60	73.0	71.4	23.4	22.4	15.1	19.4
1.60 – 2.20	75.2	76.5	28.0	27.1	23.7	28.1
2.20 – 3.00	75.9	73.4	39.5	37.4	37.6	43.4
3.00 – 4.00	74.7	71.3	50.3	47.4	49.9	54.2
4.00 – 5.50	71.5	70.9	64.3	60.5	62.0	65.2
5.50 – 7.00	73.0	65.4	73.4	68.1	70.6	73.1
7.00 – 10.00	66.5	58.9	76.0	71.9	71.8	74.4
E1 (0.30 – 1.0)	47.5	41.1	11.0	10.3	3.3	6.3
E2 (1.0 – 3.0)	72.9	71.9	26.8	25.3	21.7	26.0
E3 (3.0 – 10.0)	71.4	66.6	66.0	62.0	63.6	66.7
MERV rating from vendor	11	11	11	11	11	11
MERV rating from testing	8	7	7	7	7	7

Table G-8. Measured Pressure Drops During Aging of a Commercial 24" x 24" x 2" Pleated Electrostatic Filter (C15AAA-11)

Weeks of Use (hours of operation)	**Mass Gained** (g)	**Measured Pressure Drop** (in. w.g.)			
		984 cfm (246 fpm)	**1476 cfm** (369 fpm)	**1968 cfm** (492 fpm)	**2460 cfm** (615 fpm)
0 (0) (12” x 24” filter)	0	0.14	0.25	0.40	0.59
0 (0)	0	0.13	0.22	0.34	0.47
2 (336)	13	0.14	0.24	0.37	0.53
4 (672)	24	0.14	0.25	0.38	0.54
8 (1,344)	42	0.15	0.26	0.39	0.55
16 (2,688)	89	0.18	0.30	0.46	0.64
Manufacturer’s Pressure Drop Data (in. w.g.)		0.12 at 250 fpm	0.23 at 375 fpm	0.38 at 500 fpm	0.51 at 625 fpm

Table G-9. Measured Collection Efficiencies During Aging of a Commercial 24" x 24" x 12" Pleated Electrostatic Box Filter (C8GZ-13)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)					
	0 weeks (Test 1)	0 weeks (Test 2)	2 weeks	4 weeks	8 weeks	16 weeks
0.029	74.8	65.5	70.4	66.3	59.9	56.8
0.034	73.0	64.7	65.4	61.8	53.9	52.4
0.039	72.9	60.1	63.1	57.2	50.8	47.7
0.045	73.2	61.5	61.1	53.4	46.6	42.3
0.052	72.2	58.3	58.1	48.7	42.0	37.2
0.060	70.8	59.4	55.5	46.7	39.4	34.1
0.070	69.6	58.8	51.7	42.1	36.2	32.3
0.081	68.2	55.4	49.7	39.3	32.4	28.4
0.093	68.8	56.3	47.1	36.4	31.1	25.9
0.11	66.1	53.6	44.6	32.6	30.0	23.9
0.12	65.4	53.8	42.3	32.0	29.1	23.9
0.14	65.4	52.0	41.8	30.8	30.3	22.8
0.17	64.7	52.5	41.1	29.5	29.3	20.9
0.19	63.7	53.7	38.2	28.9	30.9	20.0
0.22	63.2	50.4	40.5	29.4	31.8	21.5
0.26	63.2	53.4	38.8	27.2	31.8	24.5
0.29	60.3	53.9	37.7	33.1	32.7	28.1
0.30 – 0.40	60.9	66.3	36.2	30.0	25.4	20.6
0.40 – 0.55	66.4	73.8	42.8	34.8	31.5	23.8
0.55 – 0.70	72.5	81.7	48.9	41.5	37.2	29.7
0.70 – 1.00	77.7	88.3	56.2	48.4	44.5	35.8
1.00 – 1.30	82.3	94.0	62.3	54.9	51.9	41.9
1.30 – 1.60	85.5	96.1	67.1	61.0	57.4	46.9
1.60 – 2.20	90.1	97.2	76.5	71.8	68.8	56.9
2.20 – 3.00	95.2	97.9	87.3	85.0	83.2	69.0
3.00 – 4.00	97.3	98.2	93.0	91.5	90.7	77.2
4.00 – 5.50	98.5	98.4	96.7	96.3	95.8	89.1
5.50 – 7.00	99.2	98.2	98.1	98.0	98.0	95.5
7.00 – 10.00	99.6	100.0	98.8	98.8	99.0	97.5
E1 (0.30 – 1.0)	69.4	77.5	46.0	38.7	34.6	27.5
E2 (1.0 – 3.0)	88.3	96.3	73.3	68.2	65.3	53.7
E3 (3.0 – 10.0)	98.6	98.7	96.6	69.2	95.9	89.8
MERV rating from vendor	13	13	13	13	13	13
MERV rating from testing	12	14	11	11	11	10

Table G-10. Measured Pressure Drops During Aging of a Commercial 24" x 24" x 12" Pleated Electrostatic Box Filter (C8GZ-13)

Weeks of Use (hours of operation)	**Mass Gained** (g)	**Measured Pressure Drop** (in. w.g.)			
		984 cfm (246 fpm)	**1476 cfm** (369 fpm)	**1968 cfm** (492 fpm)	**2460 cfm** (615 fpm)
0 (0) (Test 1)	0	0.25	0.40	0.59	0.80
0 (0) (Test 2)	0	0.26	0.43	0.63	0.89
2 (336)	9	0.25	0.41	0.59	0.80
4 (672)	14	0.25	0.40	0.57	0.79
8 (1,344)	32	0.25	0.40	0.57	0.78
16 (2,688)	50	0.25	0.40	0.58	0.78
Manufacturer's Pressure Drop Data (in. w.g.)		NA	NA	0.44 at 500 fpm	NA

Table G-11. Measured Collection Efficiencies During Aging of a Commercial 24" x 24" x 12" Pleated Non-Electrostatic Filter (C14PCS)

Particle Size Range or Midpoint of Range (μm)	Particle Size Efficiency (%)				
	0 weeks	2 weeks	4 weeks	8 weeks	16 weeks
0.029	85.4	85.9	82.9	88.3	88.8
0.034	83.6	83.3	81.4	86.2	88.1
0.039	80.3	80.8	77.9	83.9	87.4
0.045	77.1	78.0	76.0	80.7	85.5
0.052	73.7	74.8	72.1	78.3	84.3
0.060	71.5	71.7	69.3	75.7	82.5
0.070	67.5	69.3	66.1	73.0	81.9
0.081	65.3	66.6	63.3	70.3	81.1
0.093	63.6	64.6	62.0	69.2	80.0
0.11	61.1	63.5	60.8	68.2	79.9
0.12	60.6	63.5	60.5	67.3	80.6
0.14	61.7	63.5	60.3	68.2	81.4
0.17	61.6	65.1	62.0	68.5	82.5
0.19	60.0	65.3	61.6	69.1	82.8
0.22	63.8	69.0	65.5	72.1	83.9
0.26	64.3	67.8	64.6	72.9	85.4
0.29	66.6	68.5	64.7	75.0	86.9
0.30 – 0.40	62.0	72.1	64.5	70.8	77.0
0.40 – 0.55	68.6	76.9	70.7	75.9	80.7
0.55 – 0.70	74.4	81.3	75.9	80.5	86.4
0.70 – 1.00	80.2	85.5	81.5	85.1	91.2
1.00 – 1.30	84.0	88.4	85.7	87.9	95.5
1.30 – 1.60	86.7	90.6	87.9	90.0	96.8
1.60 – 2.20	91.3	93.8	91.8	93.2	98.1
2.20 – 3.00	95.7	97.1	95.8	96.5	98.7
3.00 – 4.00	97.6	98.4	97.6	97.9	98.9
4.00 – 5.50	98.6	99.2	98.5	98.6	99.1
5.50 – 7.00	99.1	99.9	99.0	99.1	99.4
7.00 – 10.00	99.3	100.0	99.4	99.3	100.0
E1 (0.30 – 1.0)	71.3	79.0	73.2	78.1	83.8
E2 (1.0 – 3.0)	89.4	92.5	90.3	91.9	97.3
E3 (3.0 – 10.0)	98.6	99.4	98.6	98.7	99.3
MERV rating from vendor	14	14	14	14	14
MERV rating from testing	12	14	13	14	14

Table G-12. Measured Pressure Drops During Aging of a Commercial 24" x 24" x 12" Pleated Non-Electrostatic Filter (C14PCS)

Weeks of Use (hours of operation)	**Mass Gained** (g)	**Measured Pressure Drop** (in. w.g.)			
		984 cfm (246 fpm)	**1476 cfm** (369 fpm)	**1968 cfm** (492 fpm)	**2460 cfm** (615 fpm)
0 (0)	0	0.24	0.41	0.60	0.83
2 (336)	17	0.25	0.42	0.62	0.84
4 (672)	26	0.26	0.42	0.62	0.84
8 (1,344)	39	0.27	0.44	0.64	0.87
16 (2,688)	76	0.28	0.46	0.66	0.89
Manufacturer's Pressure Drop Data (in. w.g.)		0.25 at 250 fpm	0.40 at 375 fpm	0.60 at 500 fpm	0.78 at 625 fpm

Table G-13. Measured Collection Efficiencies During Aging of a Commercial 24" x 24" x 12" Pleated Non-Electrostatic Filter (C11GM-16)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)				
	0 weeks	2 weeks	4 weeks	8 weeks	16 weeks
0.029	99.9	99.7	99.8	99.8	99.9
0.034	99.8	99.6	99.8	99.6	99.8
0.039	99.7	99.5	99.5	99.5	99.5
0.045	99.4	99.4	99.3	99.3	99.4
0.052	99.0	99.3	98.9	98.8	98.9
0.060	98.4	99.0	98.5	98.3	98.4
0.070	97.7	98.7	97.8	97.6	97.8
0.081	96.9	98.5	97.1	96.8	97.2
0.093	96.2	98.1	96.5	96.1	96.4
0.11	95.6	98.0	95.9	95.4	95.9
0.12	95.0	97.6	95.1	94.8	95.2
0.14	94.9	97.5	95.0	94.3	94.9
0.17	94.9	97.3	95.1	94.8	94.9
0.19	95.2	97.3	95.0	95.1	95.0
0.22	94.9	97.5	95.5	95.4	95.6
0.26	95.1	97.3	95.6	96.0	95.7
0.29	96.3	97.6	95.9	95.9	96.7
0.30 – 0.40	97.0	97.0	97.2	97.5	98.1
0.40 – 0.55	98.4	98.4	98.6	98.6	99.2
0.55 – 0.70	99.2	99.2	99.3	99.2	99.7
0.70 – 1.00	99.6	99.6	99.7	99.5	99.9
1.00 – 1.30	99.8	99.8	99.8	99.8	99.9
1.30 – 1.60	99.9	99.9	99.9	99.9	100.0
1.60 – 2.20	99.9	99.9	99.9	99.9	100.0
2.20 – 3.00	100.0	100.0	100.0	99.9	100.0
3.00 – 4.00	100.0	100.0	100.0	99.9	100.0
4.00 – 5.50	100.0	100.0	100.0	99.9	100.0
5.50 – 7.00	100.0	100.0	100.0	99.9	100.0
7.00 – 10.00	100.0	100.0	100.0	99.9	100.0
E1 (0.30 – 1.0)	98.6	98.5	98.7	98.7	99.2
E2 (1.0 – 3.0)	99.9	99.9	99.9	99.9	100
E3 (3.0 – 10.0)	100	100	100	99.9	100
MERV rating from vendor	16	16	16	16	16
MERV rating from testing	16	16	16	16	16

Table G-14. Measured Pressure Drops During Aging of a Commercial 24" x 24" x 12" Pleated Non-Electrostatic Filter (C11GM-16)

Weeks of Use (hours of operation)	**Mass Gained** (g)	**Measured Pressure Drop** (in. w.g.)			
		984 cfm (246 fpm)	**1476 cfm** (369 fpm)	**1968 cfm** (492 fpm)	**2460 cfm** (615 fpm)
0 (0)	0	0.37	0.59	0.85	1.14
2 (336)	11	0.36	0.58	0.84	1.13
4 (672)	22	0.35	0.57	0.83	1.11
8 (1,344)	42	0.36	0.58	0.83	1.12
16 (2,688)	81	0.37	0.60	0.86	1.16
Manufacturer's Pressure Drop Data (in. w.g.)		0.42 at 250 fpm	0.55 at 375 fpm	0.61 at 500 fpm	NA

Table G-15. Measured Collection Efficiencies During Aging of a Residential Electronic Air Cleaner (Unit A)

Particle Size Range or Midpoint of Range (μm)	Particle Size Efficiency (%)				
	0 weeks	2 weeks	4 weeks	8 weeks	16 weeks
0.029	93.1	91.7	90.8	84.0	81.4
0.034	92.5	90.6	90.7	82.3	81.1
0.039	92.3	90.7	90.8	81.8	80.6
0.045	91.6	90.4	91.3	80.8	80.2
0.052	91.0	89.3	91.3	79.7	79.6
0.060	90.5	88.9	91.1	77.8	78.5
0.070	89.7	87.5	91.3	77.1	77.5
0.081	89.0	87.2	90.8	75.8	76.7
0.093	88.3	86.2	90.4	74.7	76.5
0.11	88.1	86.1	90.3	72.2	76.1
0.12	87.3	85.9	90.2	71.6	75.4
0.14	86.8	85.7	90.2	69.7	75.5
0.17	85.6	84.8	89.8	69.5	76.5
0.19	85.0	84.6	89.4	69.3	76.9
0.22	84.2	83.2	89.4	70.3	77.4
0.26	84.7	83.4	89.2	70.3	79.2
0.29	83.5	84.3	88.8	70.6	79.2
0.30 – 0.40	80.8	85.6	84.4	77.5	73.4
0.40 – 0.55	82.8	87.2	86.4	81.6	77.8
0.55 – 0.70	85.4	89.2	88.6	85.2	83.3
0.70 – 1.00	87.7	91.1	90.8	88.7	88.1
1.00 – 1.30	90.6	93.0	93.2	91.8	92.0
1.30 – 1.60	91.9	94.0	94.3	92.9	93.4
1.60 – 2.20	94.1	95.0	95.4	94.2	94.5
2.20 – 3.00	95.6	96.1	96.2	95.5	95.1
3.00 – 4.00	96.7	96.9	97.0	96.3	95.9
4.00 – 5.50	97.8	97.3	98.0	96.8	96.8
5.50 – 7.00	98.0	97.9	98.4	97.7	96.7
7.00 – 10.00	99.2	97.0	99.5	96.4	97.6
E1 (0.30 – 1.0)	84.2	88.3	87.6	83.2	80.7
E2 (1.0 – 3.0)	93.1	94.5	94.8	93.6	93.8
E3 (3.0 – 10.0)	97.9	97.3	98.2	96.8	96.8
MERV rating from vendor	15	15	15	15	15
MERV rating from testing	14	15	15	14	14

Table G-16. Measured Pressure Drops During Aging of a Residential Electronic Air Cleaner (Unit A)

Weeks of Use (hours of operation)	**Measured Pressure Drop** (in. w.g.)			
	410 cfm (148 fpm)	**614 cfm** (221 fpm)	**820 cfm** (295 fpm)	**1024 cfm** (369 fpm)
0 (0)	0.05	0.08	0.12	0.17
1 (168)	0.06	0.10	0.16	0.24
2 (336)	0.06	0.08	0.12	0.17
6 (1,008)	0.07	0.11	0.16	0.22
12 (2,016)	0.08	0.11	0.15	0.17
Manufacturer's Pressure Drop Data (in. w.g.)	NA	NA	0.10 at 360 fpm	0.17 at 504 fpm

Table G-17. Measured Collection Efficiencies During Aging of a Residential Electronic Air Cleaner (Unit H)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)				
	0 weeks	2 weeks	4 weeks	8 weeks	16 weeks
0.029	93.8	93.0	91.8	77.6	64.5
0.034	94.5	94.3	92.3	82.4	67.7
0.039	94.8	94.1	92.0	84.5	71.5
0.045	94.4	93.5	91.1	85.1	72.4
0.052	93.6	92.6	90.0	84.2	71.4
0.060	92.8	91.9	89.0	82.9	70.3
0.070	91.9	90.2	88.6	82.1	67.9
0.081	91.4	88.3	87.1	80.8	66.2
0.093	90.2	86.8	86.4	79.8	64.2
0.11	89.4	86.0	86.1	78.1	62.8
0.12	88.8	85.7	85.9	77.5	61.5
0.14	88.5	86.5	85.3	76.4	60.5
0.17	87.2	86.4	85.9	77.2	60.0
0.19	88.5	86.7	86.4	77.2	61.0
0.22	87.8	85.7	86.1	78.1	59.8
0.26	87.5	85.8	87.1	79.0	62.0
0.29	87.1	86.0	87.3	79.9	62.3
0.30 – 0.40	89.3	88.7	90.0	80.0	67.9
0.40 – 0.55	91.9	91.7	92.9	85.3	71.4
0.55 – 0.70	94.0	94.3	94.9	89.5	77.3
0.70 – 1.00	95.5	95.8	96.0	92.5	82.3
1.00 – 1.30	96.5	96.8	96.8	94.4	86.6
1.30 – 1.60	96.6	97.1	97.1	95.1	88.8
1.60 – 2.20	97.1	97.4	97.2	95.9	90.4
2.20 – 3.00	97.4	97.7	97.7	96.7	91.9
3.00 – 4.00	97.6	97.9	98.1	97.5	93.6
4.00 – 5.50	98.0	98.1	98.4	97.9	94.6
5.50 – 7.00	98.0	98.2	98.3	99.1	94.8
7.00 – 10.00	98.8	99.1	98.0	97.8	95.3
E1 (0.30 – 1.0)	92.7	92.6	93.4	86.8	74.7
E2 (1.0 – 3.0)	96.9	97.3	97.2	95.6	89.4
E3 (3.0 – 10.0)	98.1	98.3	98.2	98.1	94.6
MERV rating from vendor	12 at 492 fpm	12 at 492 fpm	12 at 492 fpm	12 at 492 fpm	12 at 492 fpm
MERV rating from testing	15	15	15	15	12

Table G-18. Measured Pressure Drops During Aging of a Residential Electronic Air Cleaner (Unit H)

Weeks of Use (hours of operation)	**Measured Pressure Drop** (in. w.g.)			
	410 cfm (148 fpm)	**614 cfm** (221 fpm)	**820 cfm** (295 fpm)	**1024 cfm** (369 fpm)
0 (0)	0.03	0.06	0.11	0.17
1 (168)	0.03	0.06	0.09	0.13
2 (336)	0.05	0.09	0.13	0.18
6 (1,008)	0.05	0.09	0.13	0.20
12 (2,016)	0.05	0.08	0.13	0.19
Manufacturer's Pressure Drop Data (in. w.g.)	0.03 at 148 fpm	0.04 at 221 fpm	0.06 at 295 fpm	0.09 at 369 fpm

Table G-19. Measured Collection Efficiencies During Aging of a Residential Electronic Air Cleaner (Unit P)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)				
	0 weeks	2 weeks	4 weeks	8 weeks	16 weeks
0.029	81.2	83.9	76.3	47.7	21.7
0.034	84.4	86.6	77.9	47.4	26.1
0.039	88.2	87.6	78.0	48.5	23.0
0.045	88.5	87.0	77.6	45.4	24.0
0.052	87.9	86.0	76.5	41.4	20.8
0.060	86.7	85.3	74.0	37.8	17.9
0.070	85.5	82.7	72.7	34.6	13.4
0.081	83.7	81.0	70.9	30.8	9.7
0.093	81.7	78.7	68.7	26.2	8.1
0.11	80.9	77.3	67.7	24.7	7.1
0.12	80.1	76.3	67.1	22.6	6.4
0.14	78.5	76.1	66.8	18.3	4.1
0.17	79.0	75.1	66.3	17.7	4.9
0.19	77.5	74.3	67.1	14.4	3.7
0.22	80.0	73.2	67.5	13.6	2.7
0.26	79.7	74.3	67.1	10.5	2.7
0.29	80.8	72.2	67.9	10.1	0.0
0.30 – 0.40	76.7	74.1	69.6	15.6	5.1
0.40 – 0.55	82.1	80.0	76.0	17.4	4.3
0.55 – 0.70	86.5	85.4	81.7	19.0	3.3
0.70 – 1.00	90.5	89.5	86.7	21.5	3.9
1.00 – 1.30	93.6	93.0	90.8	24.8	5.4
1.30 – 1.60	94.9	94.3	92.6	25.6	4.9
1.60 – 2.20	95.7	95.3	94.1	28.3	6.5
2.20 – 3.00	96.2	96.4	95.3	32.1	5.6
3.00 – 4.00	96.6	97.1	96.1	37.8	12.8
4.00 – 5.50	97.0	97.2	96.7	44.8	18.6
5.50 – 7.00	97.6	97.9	96.9	48.0	24.9
7.00 – 10.00	97.1	98.4	97.4	56.5	31.0
E1 (0.30 – 1.0)	84.0	82.3	78.5	18.4	4.1
E2 (1.0 – 3.0)	95.1	94.7	93.2	27.7	5.6
E3 (3.0 – 10.0)	97.1	97.6	96.8	46.8	21.8
MERV rating from vendor	NA	NA	NA	NA	NA
MERV rating from testing	14	14	14	6	5

Table G-20. Measured Pressure Drops During Aging of a Residential Electronic Air Cleaner (Unit P)

Weeks of Use (hours of operation)	**Measured Pressure Drop** (in. w.g.)			
	410 cfm (148 fpm)	**614 cfm** (221 fpm)	**820 cfm** (295 fpm)	**1024 cfm** (369 fpm)
0 (0)	0.02	0.04	0.06	0.09
1 (168)	0.02	0.03	0.05	0.06
2 (336)	0.02	0.03	0.05	0.08
6 (1,008)	0.03	0.04	0.07	0.10
12 (2,016)	0.02	0.04	0.06	0.08
Manufacturer's Pressure Drop Data (in. w.g.)	NA	NA	NA	0.11 at 504 fpm

Appendix H
Results from the Inert Aerosol Evaluations of the Conditioned Air Cleaners

Table H-1. Measured Collection Efficiencies During Conditioning of a Residential 16" x 25" x 1" Pleated Electrostatic Filter (6DDUE-8)

Particle Size Range or Midpoint of Range (μm)	Particle Size Efficiency (%)			
	Unloaded	After CT of $3.2 * 10^7$ (particles*min) / cm3	After CT of $6.9 * 10^7$ (particles*min) / cm3	After CT of $1.0 * 10^8$ (particles*min) / cm^3
0.029	25.0	16.9	20.6	14.7
0.034	33.8	27.4	32.4	24.2
0.039	30.8	26.6	29.1	20.4
0.045	28.0	22.9	26.8	17.6
0.052	27.1	22.6	24.0	17.2
0.060	25.7	21.3	23.5	17.0
0.070	23.0	18.8	23.4	14.8
0.081	22.3	17.0	21.5	15.7
0.093	22.3	17.0	21.2	15.4
0.11	23.6	18.2	22.6	15.8
0.12	23.3	17.2	22.9	15.5
0.14	23.2	15.1	22.4	16.1
0.17	21.8	14.3	21.5	14.0
0.19	25.4	16.1	23.1	17.3
0.22	25.3	13.8	23.9	15.3
0.26	18.2	8.0	17.3	8.0
0.29	18.1	4.3	14.2	7.9
0.30 – 0.40	16.1	12.0	9.0	12.3
0.40 – 0.55	14.0	10.4	9.1	12.9
0.55 – 0.70	21.4	16.3	14.9	21.6
0.70 – 1.00	31.1	30.8	29.4	36.7
1.00 – 1.30	44.8	51.0	50.1	59.3
1.30 – 1.60	50.6	64.6	63.6	70.3
1.60 – 2.20	55.6	77.6	77.7	83.2
2.20 – 3.00	56.8	86.2	85.4	88.9
3.00 – 4.00	57.6	90.3	87.8	91.3
4.00 – 5.50	55.5	90.0	89.0	92.3
5.50 – 7.00	59.2	88.4	87.7	93.0
7.00 – 10.00	54.9	86.5	84.8	92.9
E1 (0.30 – 1.0)	20.6	17.4	15.6	20.9
E2 (1.0 – 3.0)	51.9	69.9	69.2	75.4
E3 (3.0 – 10.0)	56.8	88.8	87.3	92.4
MERV rating from vendor	8	8	8	8
MERV rating from testing	7	11	11	11

Table H-2. Measured Collection Efficiencies During Conditioning of a Residential 16" x 25" x 1" Pleated Electrostatic Filter (8NM-10)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)			
	Unloaded	After CT of 5.0 * 10^7 (particles*min) / cm3	After CT of 7.5 * 10^7 (particles*min) / cm3	After CT of 1.1 * 10^8 (particles*min) / cm3
0.029	22.7	12.7	18.8	
0.034	20.2	9.8	17.4	
0.039	18.5	6.9	15.0	
0.045	17.9	7.4	13.9	
0.052	15.5	5.9	14.0	
0.060	13.8	4.7	12.7	
0.070	13.1	2.8	11.5	
0.081	13.1	2.9	10.1	
0.093	11.8	1.8	11.2	
0.11	10.8	1.1	9.5	
0.12	9.4	1.1	6.8	
0.14	10.6	1.3	9.1	
0.17	10.0	0.0	9.1	
0.19	7.9	0.0	10.9	
0.22	13.6	5.8	13.4	
0.26	12.6	0.5	13.5	
0.29	18.0	7.2	20.0	
0.30 – 0.40	16.9	5.9	16.5	33.3
0.40 – 0.55	20.5	15.0	20.6	33.9
0.55 – 0.70	33.8	28.8	34.4	49.2
0.70 – 1.00	53.7	49.0	54.5	68.1
1.00 – 1.30	72.4	68.3	73.2	83.3
1.30 – 1.60	80.4	76.8	80.5	87.8
1.60 – 2.20	86.8	84.1	85.7	91.9
2.20 – 3.00	89.8	86.8	88.2	94.0
3.00 – 4.00	91.0	87.7	88.3	95.2
4.00 – 5.50	91.5	86.8	87.7	94.8
5.50 – 7.00	91.3	85.5	87.3	93.6
7.00 – 10.00	91.8	83.0	84.4	93.2
E1 (0.30 – 1.0)	31.2	24.7	31.5	46.1
E2 (1.0 – 3.0)	82.4	79.0	81.9	89.3
E3 (3.0 – 10.0)	91.4	85.8	86.9	94.2
MERV rating from vendor	10	10	10	10
MERV rating from testing	12	11	11	12

Table H-3. Measured Collection Efficiencies During Conditioning of a Commercial 24" x 24" x 2" Pleated Electrostatic Filter (C17FPP-8)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)		
	Unloaded	After CT of 3.2 * 10^7 (particles*min) / cm3	After CT of 6.6 * 10^7 (particles*min) / cm3
0.029	29.7	38.6	17.0
0.034	34.8	31.0	13.2
0.039	30.1	33.1	16.6
0.045	28.0	30.3	12.0
0.052	22.0	26.7	14.3
0.060	20.9	29.5	17.1
0.070	17.5	24.5	15.3
0.081	18.4	24.8	16.7
0.093	14.4	21.5	18.6
0.11	12.7	21.2	19.9
0.12	11.9	22.9	16.4
0.14	15.3	17.5	18.6
0.17	12.0	13.6	19.8
0.19	13.5	25.1	24.4
0.22	8.1	16.3	15.4
0.26	15.0	24.9	28.8
0.29	16.4	22.2	26.0
0.30 – 0.40	34.5	37.9	39.6
0.40 – 0.55	39.9	41.1	40.7
0.55 – 0.70	52.3	55.9	54.2
0.70 – 1.00	66.7	72.0	72.3
1.00 – 1.30	86.7	90.0	90.1
1.30 – 1.60	90.6	94.3	93.6
1.60 – 2.20	93.3	96.7	96.3
2.20 – 3.00	93.8	97.5	98.2
3.00 – 4.00	92.2	97.9	98.2
4.00 – 5.50	89.0	98.5	97.9
5.50 – 7.00	62.7	NA	NA
7.00 – 10.00	NA	NA	NA
E1 (0.30 – 1.0)	48.3	51.7	51.7
E2 (1.0 – 3.0)	91.1	94.6	94.6
E3 (3.0 – 10.0)	81.3	98.2	98.0
MERV rating from vendor	8	8	8
MERV rating from testing	8	13	13

Table H-4. Measured Collection Efficiencies During Conditioning of a Commercial 24" x 24" x 2" Pleated Electrostatic Filter (C15AAA-11)

Particle Size Range or Midpoint of Range (μm)	Particle Size Efficiency (%)			
	Unloaded	After CT of $3.2 * 10^7$ (particles*min) / cm3	After CT of $8.0 * 10^7$ (particles*min) / cm3	After CT of $1.1 * 10^8$ (particles*min) / cm3
0.029	45.1	9.9	23.2	16.8
0.034	50.7	11.4	23.8	24.9
0.039	48.1	11.7	22.8	24.8
0.045	44.1	9.6	18.2	22.1
0.052	42.1	11.7	15.0	19.3
0.060	39.5	10.9	12.6	18.1
0.070	34.4	9.5	11.5	16.5
0.081	32.1	9.7	9.9	15.3
0.093	29.3	11.8	10.6	14.9
0.11	29.1	10.7	8.8	15.9
0.12	26.1	9.4	6.9	14.4
0.14	25.1	10.3	3.8	13.5
0.17	21.8	8.3	2.0	10.3
0.19	22.9	10.6	3.1	12.1
0.22	22.2	10.0	2.4	10.5
0.26	16.1	12.7	0.0	2.6
0.29	17.3	11.7	0.0	0.0
0.30 – 0.40	29.0	13.7	10.8	8.1
0.40 – 0.55	35.6	23.6	18.9	20.0
0.55 – 0.70	47.1	36.6	31.1	33.6
0.70 – 1.00	52.6	44.2	37.8	41.1
1.00 – 1.30	66.4	63.1	56.8	60.6
1.30 – 1.60	71.4	72.6	67.7	69.8
1.60 – 2.20	76.5	83.4	78.3	81.0
2.20 – 3.00	73.4	85.6	80.4	81.8
3.00 – 4.00	71.3	86.6	80.8	82.7
4.00 – 5.50	70.9	88.2	81.0	83.4
5.50 – 7.00	65.4	88.8	78.9	86.2
7.00 – 10.00	58.9	90.7	78.5	87.7
E1 (0.30 – 1.0)	41.1	29.5	24.6	25.7
E2 (1.0 – 3.0)	71.9	76.2	70.8	73.3
E3 (3.0 – 10.0)	66.6	88.6	79.8	85.0
MERV rating from vendor	11	11	11	11
MERV rating from testing	7	11	8	11

Table H-5. Measured Collection Efficiencies During Conditioning of a Commercial 24" x 24" x 12" Pleated Electrostatic Box Filter (C8GZ-13)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)			
	Unloaded	After CT of $3.2 * 10^7$ (particles*min) / cm3	After CT of $6.4 * 10^7$ (particles*min) / cm3	After CT of $9.6 * 10^7$ (particles*min) / cm3
0.029	65.5	72.7	76.4	77.6
0.034	64.7	74.3	75.0	76.9
0.039	60.1	72.9	72.2	76.4
0.045	61.5	72.3	72.1	76.7
0.052	58.3	72.2	68.8	73.1
0.060	59.4	69.2	69.1	73.8
0.070	58.8	72.0	69.3	74.1
0.081	55.4	70.3	65.6	71.6
0.093	56.3	65.2	64.7	70.5
0.11	53.6	66.2	63.5	69.8
0.12	53.8	64.2	61.7	67.7
0.14	52.0	63.0	61.3	70.1
0.17	52.5	61.7	60.7	66.5
0.19	53.7	61.2	59.7	66.4
0.22	50.4	62.9	59.7	69.7
0.26	53.4	58.4	59.9	65.2
0.29	53.9	56.7	58.6	67.2
0.30 – 0.40	66.3	59.5	63.7	60.0
0.40 – 0.55	73.8	69.4	70.7	68.6
0.55 – 0.70	81.7	79.0	80.1	78.3
0.70 – 1.00	88.3	87.0	87.7	86.5
1.00 – 1.30	94.0	93.9	94.4	93.8
1.30 – 1.60	96.1	96.3	96.6	96.5
1.60 – 2.20	97.2	97.9	98.1	98.0
2.20 – 3.00	97.9	98.6	98.5	98.5
3.00 – 4.00	98.2	98.8	98.7	98.6
4.00 – 5.50	98.4	98.9	98.8	98.6
5.50 – 7.00	98.2	98.2	96.9	99.1
7.00 – 10.00	100.0			
E1 (0.30 – 1.0)	77.5	73.7	75.6	73.4
E2 (1.0 – 3.0)	96.3	96.7	96.9	96.7
E3 (3.0 – 10.0)	98.7	98.6	98.1	98.8
MERV rating from vendor	13	13	13	13
MERV rating from testing	14	13	14	13

Table H-6. Measured Collection Efficiencies During Conditioning of a Residential 16" x 25" x 1" Pleated Electrostatic Filter (5RM-11-1)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)		
	Unloaded	After CT of 3.4 * 10^7 (particles*min) / cm3	After CT of 6.6 * 10^7 (particles*min) / cm3
0.029	35.5	5.9	24.0
0.034	31.8	9.6	26.4
0.039	27.5	11.4	26.9
0.045	26.5	11.7	27.4
0.052	23.6	10.0	28.1
0.060	22.3	10.1	28.0
0.070	19.7	10.8	29.7
0.081	17.5	11.4	31.6
0.093	16.0	11.5	31.7
0.11	15.7	13.2	32.4
0.12	14.9	11.4	33.8
0.14	11.8	11.8	34.3
0.17	12.3	11.1	36.2
0.19	9.4	10.2	36.2
0.22	12.6	16.5	40.3
0.26	8.7	14.6	40.3
0.29	15.7	19.5	45.0
0.30 – 0.40	14.7	11.5	14.2
0.40 – 0.55	11.7	8.9	10.4
0.55 – 0.70	17.1	13.9	17.3
0.70 – 1.00	33.3	28.9	34.3
1.00 – 1.30	52.9	50.3	56.8
1.30 – 1.60	62.5	63.4	69.2
1.60 – 2.20	71.2	77.5	83.8
2.20 – 3.00	72.9	84.2	90.7
3.00 – 4.00	69.4	85.4	92.4
4.00 – 5.50	66.5	86.0	93.9
5.50 – 7.00	68.2	87.9	94.9
7.00 – 10.00	70.4	87.9	95.2
E1 (0.30 – 1.0)	19.2	15.8	19.1
E2 (1.0 – 3.0)	64.9	68.8	75.1
E3 (3.0 – 10.0)	68.7	86.8	94.1
MERV rating from vendor	11	11	11
MERV rating from testing	7	11	11

Table H-7. Measured Collection Efficiencies During Conditioning of a Residential 16" x 25" x 1" Pleated Electrostatic Filter (4FUA-12-3)

Particle Size Range or Midpoint of Range (μm)	Particle Size Efficiency (%)			
	Unloaded	After CT of $3.3 * 10^7$ (particles*min) / cm3	After CT of $6.8 * 10^7$ (particles*min) / cm3	After CT of $1.1 * 10^8$ (particles*min) / cm3
0.029	48.3	51.4	30.0	43.4
0.034	50.8	49.6	28.9	41.0
0.039	49.3	48.5	28.6	37.2
0.045	48.2	47.3	26.6	35.5
0.052	46.0	46.4	23.4	32.2
0.060	43.9	46.4	22.7	29.4
0.070	42.1	45.8	21.0	27.5
0.081	40.7	44.8	19.3	25.5
0.093	40.1	45.7	17.9	24.8
0.11	38.3	45.1	17.7	24.0
0.12	36.5	45.2	18.5	22.7
0.14	34.8	45.9	18.4	22.3
0.17	33.0	47.3	17.4	22.2
0.19	32.0	47.6	17.3	21.7
0.22	34.7	50.2	24.5	25.9
0.26	32.4	48.6	23.2	27.7
0.29	34.8	52.4	28.0	30.8
0.30 – 0.40	30.4	23.8	23.5	27.3
0.40 – 0.55	32.1	25.6	23.9	26.0
0.55 – 0.70	41.2	33.5	31.1	33.4
0.70 – 1.00	55.0	47.6	45.4	48.2
1.00 – 1.30	69.8	65.6	62.7	66.0
1.30 – 1.60	77.7	75.2	73.7	77.2
1.60 – 2.20	86.2	87.3	86.1	87.9
2.20 – 3.00	89.5	92.7	92.3	93.8
3.00 – 4.00	90.4	94.4	94.3	95.5
4.00 – 5.50	90.4	96.2	96.0	96.6
5.50 – 7.00	93.3	97.4	97.8	97.6
7.00 – 10.00	94.3	97.4	98.3	99.7
E1 (0.30 – 1.0)	39.7	32.6	31.0	33.7
E2 (1.0 – 3.0)	80.8	80.2	78.7	81.2
E3 (3.0 – 10.0)	92.1	96.4	96.6	97.4
MERV rating from vendor	12	12	12	12
MERV rating from testing	12	12	11	12

Table H-8. Measured Collection Efficiencies During Conditioning of a Residential 16" x 25" x 1" Pleated Electrostatic Filter (7AST-8-3)

Particle Size Range or Midpoint of Range (μm)	Particle Size Efficiency (%)			
	Unloaded	After CT of $3.2 * 10^7$ (particles*min) / cm3	After CT of $6.9 * 10^7$ (particles*min) / cm3	After CT of $1.0 * 10^8$ (particles*min) / cm3
0.029	37.2	15.0	26.2	32.0
0.034	36.6	16.1	26.4	32.3
0.039	33.7	11.5	23.7	27.9
0.045	31.8	10.1	18.8	26.3
0.052	30.3	7.6	14.7	25.5
0.060	28.6	4.1	15.6	23.2
0.070	26.7	2.5	14.7	23.2
0.081	23.9	1.0	12.0	21.5
0.093	22.6	0.0	12.1	21.0
0.11	22.8	0.0	11.8	21.8
0.12	20.4	0.0	11.1	20.8
0.14	20.5	0.0	10.7	20.0
0.17	22.5	0.0	10.2	22.7
0.19	21.6	0.0	11.2	23.7
0.22	21.0	0.0	9.4	23.6
0.26	23.8	0.0	10.6	25.4
0.29	18.3	0.0	7.5	24.7
0.30 – 0.40	9.4	6.6	13.0	19.4
0.40 – 0.55	10.8	9.5	12.5	21.3
0.55 – 0.70	19.6	17.7	20.9	33.8
0.70 – 1.00	36.2	35.1	40.4	56.4
1.00 – 1.30	54.2	56.4	63.4	76.9
1.30 – 1.60	61.7	67.9	74.1	85.7
1.60 – 2.20	67.5	78.9	84.0	92.2
2.20 – 3.00	66.9	84.7	89.5	95.5
3.00 – 4.00	64.2	86.4	91.1	96.7
4.00 – 5.50	60.4	86.3	90.3	97.8
5.50 – 7.00	62.9	85.4	89.2	99.1
7.00 – 10.00	57.8	88.4	88.5	93.0
E1 (0.30 – 1.0)	19.0	17.2	21.7	32.7
E2 (1.0 – 3.0)	62.6	72.0	77.8	87.6
E3 (3.0 – 10.0)	61.3	86.6	89.8	96.7
MERV rating from vendor	8	8	8	8
MERV rating from testing	7	11	11	12

Table H-9. Measured Collection Efficiencies and Pressure Drops During Conditioning of a Residential Electronic Air Cleaner (Unit A)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)		Measured Pressure Drop (in. w.g.)		Manufacturer's Pressure Drop Data (in. w.g.)
	Before Silicon Vapor Exposure	After Silicon Vapor Exposure	Before Silicon Vapor Exposure	After Silicon Vapor Exposure	
0.029	95.1	87.6	0.05 @ 148 fpm	0.06 @ 148 fpm	NA
0.034	95.1	87.9	0.07 @ 221 fpm	0.09 @ 221 fpm	NA
0.039	95.4	88.4	0.11 @ 295 fpm	0.13 @ 295 fpm	0.10 @ 360 fpm
0.045	95.2	88.4	0.15 @ 369 fpm	0.19 @ 369 fpm	0.17 @ 504 fpm
0.052	94.9	88.8			
0.060	94.6	87.1			
0.070	94.6	87.3			
0.081	94.2	86.9			
0.093	94.3	84.9			
0.11	94.2	85.2			
0.12	93.9	84.4			
0.14	93.7	84.5			
0.17	93.3	83.2			
0.19	93.1	84.0			
0.22	92.8	84.1			
0.26	93.7	84.5			
0.29	93.3	83.2			
0.30 – 0.40	89.3	83.9			
0.40 – 0.55	90.3	85.7			
0.55 – 0.70	91.4	87.3			
0.70 – 1.00	92.2	89.6			
1.00 – 1.30	93.4	91.8			
1.30 – 1.60	94.0	93.2			
1.60 – 2.20	94.8	94.6			
2.20 – 3.00	95.4	96.2			
3.00 – 4.00	96.1	97.3			
4.00 – 5.50	96.9	98.0			
5.50 – 7.00	97.0	98.8			
7.00 – 10.00	96.3	NA			
E1 (0.30 – 1.0)	90.8	86.6			
E2 (1.0 – 3.0)	94.4	93.9			
E3 (3.0 – 10.0)	96.6	98.1			
MERV rating from vendor	15	15			
MERV rating from testing	15	15			

Table H-10. Measured Collection Efficiencies and Pressure Drops During Conditioning of a Residential Electronic Air Cleaner (Unit H)

Particle Size Range or Midpoint of Range (µm)	Particle Size Efficiency (%)		Measured Pressure Drop (in. w.g.)		Manufacturer's Pressure Drop Data (in. w.g.)
	Before Silicon Vapor Exposure	After Silicon Vapor Exposure	Before Silicon Vapor Exposure	After Silicon Vapor Exposure	
0.029	92.2	67.8	0.03 @ 148 fpm	0.02 @ 148 fpm	0.03 at 148 fpm
0.034	94.0	69.2	0.06 @ 221 fpm	0.03 @ 221 fpm	0.04 at 221 fpm
0.039	94.2	68.7	0.11 @ 295 fpm	0.05 @ 295 fpm	0.06 at 295 fpm
0.045	93.8	68.1	0.17 @ 369 fpm	0.07 @ 369 fpm	0.09 at 369 fpm
0.052	93.4	67.7			
0.060	92.5	63.8			
0.070	91.5	61.2			
0.081	90.5	59.1			
0.093	89.4	57.1			
0.11	88.3	57.2			
0.12	87.7	55.3			
0.14	86.6	57.8			
0.17	86.9	51.7			
0.19	87.0	56.8			
0.22	87.1	53.1			
0.26	87.3	52.5			
0.29	87.9	44.4			
0.30 – 0.40	86.8	49.3			
0.40 – 0.55	90.5	52.8			
0.55 – 0.70	93.3	54.2			
0.70 – 1.00	95.2	53.1			
1.00 – 1.30	96.5	53.3			
1.30 – 1.60	97.1	54.6			
1.60 – 2.20	97.4	55.8			
2.20 – 3.00	97.7	51.4			
3.00 – 4.00	98.3	50.3			
4.00 – 5.50	98.5	47.1			
5.50 – 7.00	98.9	44.0			
7.00 – 10.00	99.5	NA			
E1 (0.30 – 1.0)	91.5	52.3			
E2 (1.0 – 3.0)	97.2	53.8			
E3 (3.0 – 10.0)	98.8	47.1			
MERV rating from vendor	Up to 12	Up to 12			
MERV rating from testing	15	6			

Table H-11. Measured Collection Efficiencies and Pressure Drops During Conditioning of a Residential Electronic Air Cleaner (Unit P)

Particle Size Range or Midpoint of Range (μm)	Particle Size Efficiency (%)		Measured Pressure Drop (in. w.g.)		Manufacturer's Pressure Drop Data (in. w.g.)
	Before Silicon Vapor Exposure	After Silicon Vapor Exposure	Before Silicon Vapor Exposure	After Silicon Vapor Exposure	
0.029	86.4	45.2	0.03 @ 148 fpm	0.02 @ 148 fpm	NA
0.034	88.2	50.3	0.05 @ 221 fpm	0.04 @ 221 fpm	NA
0.039	89.1	47.0	0.08 @ 295 fpm	0.06 @ 295 fpm	NA
0.045	88.8	50.6	0.13 @ 369 fpm	0.09 @ 369 fpm	0.11 at 504 fpm
0.052	87.3	46.4			
0.060	86.1	42.2			
0.070	84.1	38.0			
0.081	83.1	39.5			
0.093	80.6	31.1			
0.11	80.0	35.6			
0.12	78.4	33.5			
0.14	76.9	28.4			
0.17	74.5	30.7			
0.19	74.3	32.0			
0.22	73.9	31.4			
0.26	72.9	32.4			
0.29	72.5	23.5			
0.30 – 0.40	73.9	28.2			
0.40 – 0.55	80.3	31.7			
0.55 – 0.70	85.7	35.5			
0.70 – 1.00	90.0	37.7			
1.00 – 1.30	93.7	39.7			
1.30 – 1.60	95.0	42.3			
1.60 – 2.20	96.0	45.1			
2.20 – 3.00	96.8	47.2			
3.00 – 4.00	96.9	47.9			
4.00 – 5.50	97.4	52.2			
5.50 – 7.00	97.0	51.5			
7.00 – 10.00	96.4	NA			
E1 (0.30 – 1.0)	82.5	33.3			
E2 (1.0 – 3.0)	95.3	43.6			
E3 (3.0 – 10.0)	96.9	50.5			
MERV rating from vendor	NA	NA			
MERV rating from testing	14	7			

Appendix I
Quality Assurance

Work under this task was completed in accordance with a pair of EPA approved quality assurance test plans (QAPP) entitled "Research on Air Cleaning and HVAC Systems for Protecting Buildings from Terrorist Attacks; Test/Quality Assurance Plan for Task 2: Development of Performance Information for Common Ventilation Filters," and "Research on Air Cleaning and HVAC Systems for Protecting Buildings from Terrorist Attacks; Test/Quality Assurance Plan for Task 3: Development of Performance Information for Electronic Air Cleaners." These two QAPPs described the development of the filter and electronic air cleaner tests matrices, sample acquisition and handling procedures, the inert aerosol and bioaerosol test procedures, the aging and conditioning test procedures, and the data analysis procedures. The text from the two relevant QAPPs was included in the relevant portions of this draft final comprehensive report. For example, development of the test matrices was described in

Section 2. The inert aerosol and bioaerosol test procedures were described in Sections 3.1.1 and 3.2.1, respectively. The inert aerosol and bioaerosol data analysis procedures were described in Sections 3.1.2 and 3.2.2, respectively. Sample acquisition and handling, as well as the various aging and conditioning procedures were described in Sections 3.3, 3.4, and 3.5.

In accordance with the QAPPs, an external quality assurance (QA) audit of Tasks 2/3 was performed by an EPA staff member and a designated representative on 9 August 2006 at Battelle's Columbus facility. The quality assurance inspectors reviewed the sample handling logs, standard operating procedures, test record sheets, instrument calibration sheets, data logs and data sheets from the inert and bioaerosol tests, and various other documentation. In addition, the quality assurance inspectors witnessed the performance of a bioaerosol test. Official documentation from the QA inspectors was received on 8 September 2006. In general, the auditors were pleased with the conduct of the work and had no significant findings that affected the execution of tests. A final memo was sent on 6 October 2006 in response to the findings of the auditors. No corrective actions were deemed necessary. At the completion of Tasks 2/3 all quality objectives had been achieved.

In general, the required QA calculations can be found throughout the body of this report or in the attached data CD. Three QA calculations that cannot be found in their entirety elsewhere in this report are provided below. First, as described in Section 3.2.1, for the bioaerosol tests, it was required that the air velocity uniformity and bioaerosol concentration uniformity in the text duct possess coefficients of variance of less than 25% and 30%, respectively. Table I-1 demonstrates a sample calculation showing that the air velocity unformity CV was within 25%. Tables I-2 and I-3 demonstrate a sample calculation showing that the aerosol concentration CVs were less than 25% at both the upstream and downstream sampling locations. In addition, it was required that the downstream and upstream bioaerosol mean concentrations agree within 20%. Using the ratio of the overall averages from Tables I-2 and I-3, it can be seen that the mean concentrations agreed to were within 0.5%. Lastly, for the non-standard portion of the inert aerosol tests (0.03 to 0.3 µm particle size), it was required that the aerosol concentration uniformity of the test duct possess a coefficient of variance of less than 15%. Tables I-4 and I-5 demonstrate the results from measurements of the aerosol concentration uniformity with no filter present. As shown in Tables I-4 and I-5, the results indicated that the aerosol uniformity met the requirement of a CV of less than 15% for all particle size ranges at both test velocities.

Table I-1. Air Velocity Uniformity of the Bioaerosol Test Rig (average = 210 fpm, CV = 43 fpm or 20.5%)

Air Velocity (feet per minute)		
192	239	135
262	268	218
209	209	162

Table I-2. Upstream Bioaerosol Concentration Uniformity of the Bioaerosol Test Rig (average = 5,240 CFU/L, CV = 527 CFU/L or 10.1%)

Concentration (CFU/L of air)		
5,761	4,719	4,699
5,678	4,564	4,956
5,628	5,203	5,951

Table I-3. Downstream Bioaerosol Concentration Uniformity of the Bioaerosol Test Rig (average = 5,214 CFU/L, CV = 373 CFU/L or 7.2%)

Concentration (CFU/L)		
5,367	5,332	4,840
5,220	5,328	4,442
5,210	5,737	5,451

Table I-4. Results from the Aerosol Concentration Uniformity Evaluations of Intertek's ASHRAE 52.2-1999 Test Stand at 472 CFM

Average Size (µm)	0.0255	0.0294	0.0340	0.0392	0.0453	0.0523	0.0604	0.0698	0.0806	0.0931	0.107	0.124	0.143	0.165	0.191	0.221	0.255	0.294	0.340	0.392
Grid Point	**Total Particles Counted**																			
1	1,569	2,061	2,648	3,135	3,611	3,930	4,169	4,201	4,247	3,968	3,582	3,185	2,721	2,284	1,778	1,411	1,064	780	607	446
2	1,675	2,129	2,823	3,272	3,773	4,090	4,287	4,511	4,362	4,118	3,747	3,336	2,798	2,337	1,875	1,468	1,094	865	640	499
3	2,268	2,590	3,060	3,515	3,968	4,252	4,571	4,589	4,502	4,254	3,927	3,459	2,980	2,395	1,911	1,560	1,218	897	677	539
4	2,057	2,383	2,878	3,359	3,729	4,132	4,398	4,336	4,344	4,106	3,746	3,334	2,804	2,348	1,884	1,495	1,131	846	622	508
5	1,609	2,034	2,602	3,213	3,707	4,126	4,380	4,395	4,463	4,236	3,889	3,366	2,945	2,433	1,914	1,521	1,210	906	658	520
6	1,951	2,399	3,038	3,674	4,131	4,466	4,636	4,761	4,582	4,414	4,051	3,555	3,026	2,539	1,987	1,525	1,194	935	700	547
7	1,946	2,480	3,058	3,667	3,962	4,160	4,456	4,400	4,419	4,094	3,831	3,451	2,905	2,444	1,913	1,529	1,195	905	698	519
8	1,715	2,173	2,878	3,412	3,855	4,232	4,424	4,432	4,520	4,165	3,909	3,357	2,891	2,435	1,956	1,533	1,147	877	692	513
9	1,784	2,258	2,836	3,354	3,884	4,342	4,585	4,536	4,499	4,365	3,977	3,530	3,126	2,508	2,025	1,583	1,249	958	696	519
Mean	1,842	2,278	2,869	3,400	3,847	4,192	4,434	4,462	4,437	4,191	3,851	3,397	2,911	2,414	1,916	1,514	1,167	885	666	512
St. Dev	231	195	167	189	160	154	150	161	104	141	142	114	126	82	71	51	62	52	35	29
CV	12.5%	8.6%	5.8%	5.5%	4.2%	3.7%	3.4%	3.6%	2.4%	3.4%	3.7%	3.4%	4.3%	3.4%	3.7%	3.4%	5.3%	5.9%	5.3%	5.6%

Table I-5. Results from the Aerosol Concentration Uniformity Evaluations of Intertek's ASHRAE 52.2-1999 Test Stand at 1968 CFM

Average Size (μm)	0.0255	0.0294	0.0340	0.0392	0.0453	0.0523	0.0604	0.0698	0.0806	0.0931	0.107	0.124	0.143	0.165	0.191	0.221	0.255	0.294	0.340	0.392
Grid Point	**Total Particles Counted**																			
1	327	448	544	673	710	819	855	880	866	823	737	650	527	442	369	288	218	170	128	105
2	399	505	612	692	836	840	928	942	916	882	783	721	575	483	392	306	230	184	137	96
3	421	515	634	785	883	922	949	1040	958	857	850	737	619	480	414	299	227	180	137	85
4	327	509	611	728	784	842	870	876	866	826	763	678	558	474	380	296	221	178	113	90
5	337	463	611	724	849	892	958	927	927	880	808	696	588	499	405	311	243	191	127	88
6	412	532	658	762	889	935	1028	1006	998	915	795	748	643	527	422	344	237	197	140	113
7	315	448	529	652	768	829	945	895	897	873	752	652	550	440	372	292	231	166	129	102
8	408	523	578	707	811	863	956	928	926	875	769	706	614	506	397	310	248	204	149	103
9	360	522	642	769	850	972	964	947	944	939	838	732	597	537	414	326	248	178	158	105
Mean	367	496	602	721	820	879	939	938	922	875	788	702	586	487	396	308	234	183	136	99
St. Dev	43	34	44	45	58	54	52	55	43	37	38	36	37	34	19	18	11	12	13	9
CV	11.6%	6.8%	7.3%	6.3%	7.1%	6.1%	5.5%	5.9%	4.7%	4.3%	4.8%	5.1%	6.3%	6.9%	4.9%	5.8%	4.7%	6.7%	9.6%	9.5%

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